PEARSON NEW INTERNATIONAL EDITION

Electronic Devices and Circuit Theory

Robert L. Boylestad Louis Nashelsky

Eleventh Edition

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Semiconductor Diodes

CHAPTER OBJECTIVES

- Become aware of the general characteristics of three important semiconductor materials: Si, Ge, GaAs.
- Understand conduction using electron and hole theory.
- Be able to describe the difference between *n*- and *p*-type materials.
- Develop a clear understanding of the basic operation and characteristics of a diode in the no-bias, forward-bias, and reverse-bias regions.
- Be able to calculate the dc, ac, and average ac resistance of a diode from the characteristics.
- Understand the impact of an equivalent circuit whether it is ideal or practical.
- Become familiar with the operation and characteristics of a Zener diode and light-emitting diode.

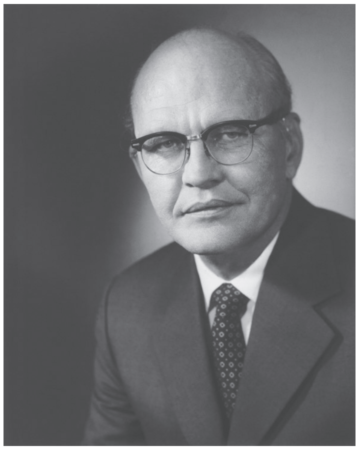
1 INTRODUCTION

One of the noteworthy things about this field, as in many other areas of technology, is how little the fundamental principles change over time. Systems are incredibly smaller, current speeds of operation are truly remarkable, and new gadgets surface every day, leaving us to wonder where technology is taking us. However, if we take a moment to consider that the majority of all the devices in use were invented decades ago and that design techniques appearing in texts as far back as the 1930s are still in use, we realize that most of what we see is primarily a steady improvement in construction techniques, general characteristics, and application techniques rather than the development of new elements and fundamentally new designs. The result is that most of the devices discussed in this text have been around for some time, and that texts on the subject written a decade ago are still good references with content that has not changed very much. The major changes have been in the understanding of how these devices work and their full range of capabilities, and in improved methods of teaching the fundamentals associated with them. The benefit of all this to the new student of the subject is that the material in this text will, we hope, have reached a level where it is relatively easy to grasp and the information will have application for years to come.

The miniaturization that has occurred in recent years leaves us to wonder about its limits. Complete systems now appear on wafers thousands of times smaller than the single element of earlier networks. The first integrated circuit (IC) was developed by Jack Kilby while working at Texas Instruments in 1958 (Fig. 1). Today, the Intel® Core™ i7 Extreme

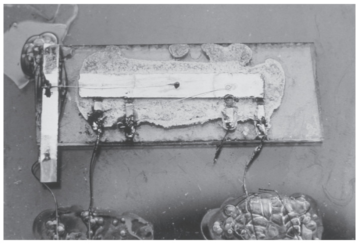
Edition Processor of Fig. 2 has 731 million transistors in a package that is only slightly larger than a 1.67 sq. inches. In 1965, Dr. Gordon E. Moore presented a paper predicting that the transistor count in a single IC chip would double every two years. Now, more than 45 years, later we find that his prediction is amazingly accurate and expected to continue for the next few decades. We have obviously reached a point where the primary purpose of the container is simply to provide some means for handling the device or system and to provide a mechanism for attachment to the remainder of the network. Further miniaturization appears to be limited by four factors: the quality of the semiconductor material, the network design technique, the limits of the manufacturing and processing equipment, and the strength of the innovative spirit in the semiconductor industry.

The first device to be introduced here is the simplest of all electronic devices, yet has a range of applications that seems endless.



Jack St. Clair Kilby, inventor of the integrated circuit and co-inventor of the electronic handheld calculator. (Courtesy of Texas Instruments.)

Born: Jefferson City, Missouri,1923. MS, University of Wisconsin. Director of Engineering and Technology, Components Group, Texas Instruments. Fellow of the IEEE. Holds more than 60 U.S. patents.



The first integrated circuit, a phase-shift oscillator, invented by Jack S. Kilby in 1958. (Courtesy of Texas Instruments.)

FIG. 1
Jack St. Clair Kilby.

2 SEMICONDUCTOR MATERIALS: Ge, Si, AND GaAs

The construction of every discrete (individual) solid-state (hard crystal structure) electronic device or integrated circuit begins with a semiconductor material of the highest quality.

Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.

In general, semiconductor materials fall into one of two classes: *single-crystal* and *compound.* Single-crystal semiconductors such as germanium (Ge) and silicon (Si) have a repetitive crystal structure, whereas compound semiconductors such as gallium arsenide (GaAs), cadmium sulfide (CdS), gallium nitride (GaN), and gallium arsenide phosphide (GaAsP) are constructed of two or more semiconductor materials of different atomic structures.

The three semiconductors used most frequently in the construction of electronic devices are Ge, Si, and GaAs.

In the first few decades following the discovery of the diode in 1939 and the transistor in 1947 germanium was used almost exclusively because it was relatively easy to find and was available in fairly large quantities. It was also relatively easy to refine to obtain very high levels of purity, an important aspect in the fabrication process. However, it was discovered in the early years that diodes and transistors constructed using germanium as the base material suffered from low levels of reliability due primarily to its sensitivity to changes in temperature. At the time, scientists were aware that another material, silicon, had improved temperature sensitivities, but the refining process for manufacturing silicon of very high levels of purity was still in the development stages. Finally, however, in 1954 the first silicon transistor was introduced, and silicon quickly became the semiconductor material of choice. Not only is silicon less temperature sensitive, but it is one of the most abundant materials on earth, removing any concerns about availability. The flood gates now opened to this new material, and the manufacturing and design technology improved steadily through the following years to the current high level of sophistication.

As time moved on, however, the field of electronics became increasingly sensitive to issues of speed. Computers were operating at higher and higher speeds, and communication systems were operating at higher levels of performance. A semiconductor material capable of meeting these new needs had to be found. The result was the development of the first GaAs transistor in the early 1970s. This new transistor had speeds of operation up to five times that of Si. The problem, however, was that because of the years of intense design efforts and manufacturing improvements using Si, Si transistor networks for most applications were cheaper to manufacture and had the advantage of highly efficient design strategies. GaAs was more difficult to manufacture at high levels of purity, was more expensive, and had little design support in the early years of development. However, in time the demand for increased speed resulted in more funding for GaAs research, to the point that today it is often used as the base material for new high-speed, very large scale integrated (VLSI) circuit designs.

This brief review of the history of semiconductor materials is not meant to imply that GaAs will soon be the only material appropriate for solid-state construction. Germanium devices are still being manufactured, although for a limited range of applications. Even though it is a temperature-sensitive semiconductor, it does have characteristics that find application in a limited number of areas. Given its availability and low manufacturing costs, it will continue to find its place in product catalogs. As noted earlier, Si has the benefit of years of development, and is the leading semiconductor material for electronic components and ICs. In fact, Si is still the fundamental building block for Intel's new line of processors.

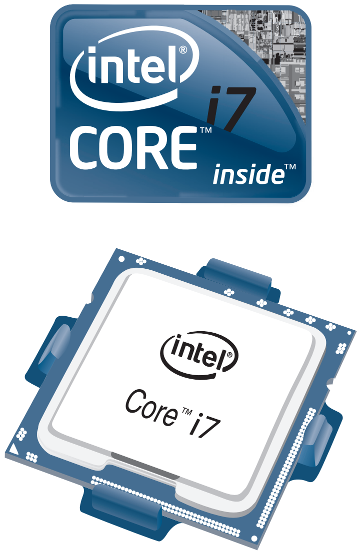


FIG. 2
Intel® Core™ i7 Extreme Edition Processor.

3 COVALENT BONDING AND INTRINSIC MATERIALS

To fully appreciate why Si, Ge, and GaAs are the semiconductors of choice for the electronics industry requires some understanding of the atomic structure of each and how the atoms are bound together to form a crystalline structure. The fundamental components of an atom are the electron, proton, and neutron. In the lattice structure, neutrons and protons form the nucleus and electrons appear in fixed orbits around the nucleus. The Bohr model for the three materials is provided in Fig. 3.

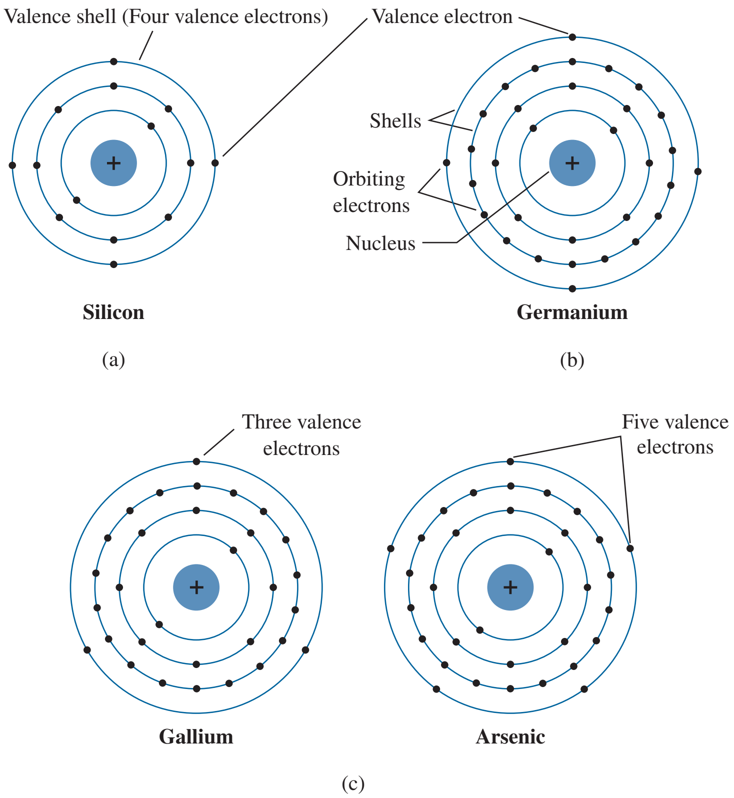


FIG. 3
Atomic structure of (a) silicon; (b) germanium; and (c) gallium and arsenic.

As indicated in Fig. 3, silicon has 14 orbiting electrons, germanium has 32 electrons, gallium has 31 electrons, and arsenic has 33 orbiting electrons (the same arsenic that is a very poisonous chemical agent). For germanium and silicon there are four electrons in the outermost shell, which are referred to as *valence electrons*. Gallium has three valence electrons and arsenic has five valence electrons. Atoms that have four valence electrons are called *tetravalent*, those with three are called *trivalent*, and those with five are called *pentavalent*. The term *valence* is used to indicate that the potential (ionization potential) required to remove any one of these electrons from the atomic structure is significantly lower than that required for any other electron in the structure.

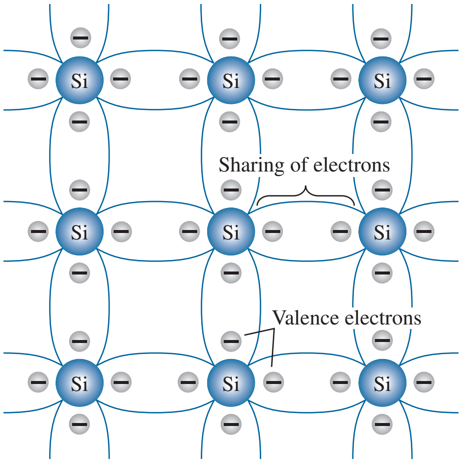


FIG. 4
Covalent bonding of the silicon atom.

In a pure silicon or germanium crystal the four valence electrons of one atom form a bonding arrangement with four adjoining atoms, as shown in Fig. 4.

This bonding of atoms, strengthened by the sharing of electrons, is called covalent bonding.

Because GaAs is a compound semiconductor, there is sharing between the two different atoms, as shown in Fig. 5. Each atom, gallium or arsenic, is surrounded by atoms of the complementary type. There is still a sharing of electrons similar in structure to that of Ge and Si, but now five electrons are provided by the As atom and three by the Ga atom.

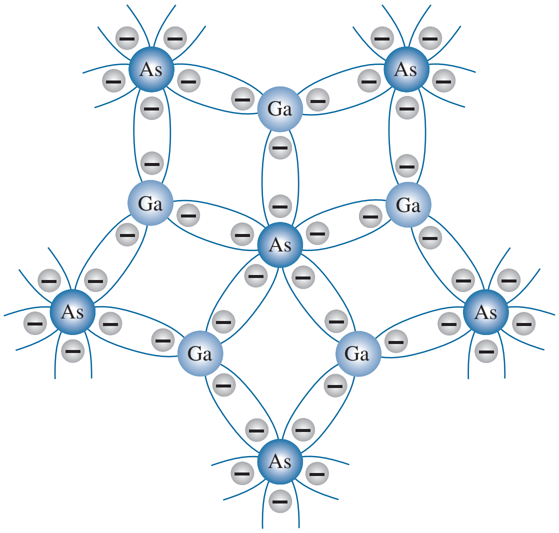


FIG. 5
Covalent bonding of the GaAs crystal.

Although the covalent bond will result in a stronger bond between the valence electrons and their parent atom, it is still possible for the valence electrons to absorb sufficient kinetic energy from external natural causes to break the covalent bond and assume the "free" state. The term *free* is applied to any electron that has separated from the fixed lattice structure and is very sensitive to any applied electric fields such as established by voltage sources or any difference in potential. *The external causes include effects such as light energy in the form of photons and thermal energy (heat) from the surrounding medium.* At room temperature there are approximately 1.5×10^{10} free carriers in 1 cm^3 of *intrinsic* silicon material, that is, 15,000,000,000 (15 billion) electrons in a space smaller than a small sugar cube—an enormous number.

The term* intrinsic *is applied to any semiconductor material that has been carefully refined to reduce the number of impurities to a very low level—essentially as pure as can be made available through modern technology.

The free electrons in a material due only to external causes are referred to as *intrinsic carriers.* Table 1 compares the number of intrinsic carriers per cubic centimeter (abbreviated n_i) for Ge, Si, and GaAs. It is interesting to note that Ge has the highest number and GaAs the lowest. In fact, Ge has more than twice the number as GaAs. The number of carriers in the intrinsic form is important, but other characteristics of the material are more significant in determining its use in the field. One such factor is the *relative mobility* (μ_n) of the free carriers in the material, that is, the ability of the free carriers to move throughout the material. Table 2 clearly reveals that the free carriers in GaAs have more than five times the mobility of free carriers in Si, a factor that results in response times using GaAs electronic devices that can be up to five times those of the same devices made from Si. Note also that free carriers in Ge have more than twice the mobility of electrons in Si, a factor that results in the continued use of Ge in high-speed radio frequency applications.

TABLE 1
Intrinsic Carriers n_i

Semiconductor	Intrinsic Carriers (per cubic centimeter)
GaAs	1.7×10^{6}
Si	1.5×10^{10}
Ge	2.5×10^{13}

TABLE 2
Relative Mobility Factor μ_n

Semiconductor	μ_n (cm^2/V·s)
Si	1500
Ge	3900
GaAs	8500

One of the most important technological advances of recent decades has been the ability to produce semiconductor materials of very high purity. Recall that this was one of the problems encountered in the early use of silicon—it was easier to produce germanium of the required purity levels. Impurity levels of 1 part in 10 billion are common today, with higher levels attainable for large-scale integrated circuits. One might ask whether these extremely high levels of purity are necessary. They certainly are if one considers that the addition of one part of impurity (of the proper type) per million in a wafer of silicon material can change that material from a relatively poor conductor to a good conductor of electricity. We obviously have to deal with a whole new level of comparison when we deal with the semiconductor medium. The ability to change the characteristics of a material through this process is called *doping*, something that germanium, silicon, and gallium arsenide readily and easily accept. The doping process is discussed in detail in Sections 5 and 6.

One important and interesting difference between semiconductors and conductors is their reaction to the application of heat. For conductors, the resistance increases with an increase in heat. This is because the numbers of carriers in a conductor do not increase significantly with temperature, but their vibration pattern about a relatively fixed location makes it increasingly difficult for a sustained flow of carriers through the material. Materials that react in this manner are said to have a *positive temperature coefficient.* Semiconductor materials, however, exhibit an increased level of conductivity with the application of heat. As the temperature rises, an increasing number of valence electrons absorb sufficient thermal energy to break the covalent bond and to contribute to the number of free carriers. Therefore:

Semiconductor materials have a negative temperature coefficient.

4 ENERGY LEVELS

Within the atomic structure of each and every *isolated* atom there are specific energy levels associated with each shell and orbiting electron, as shown in Fig. 6. The energy levels associated with each shell will be different for every element. However, in general:

The farther an electron is from the nucleus, the higher is the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.

Note in Fig. 6a that only specific energy levels can exist for the electrons in the atomic structure of an isolated atom. The result is a series of gaps between allowed energy levels

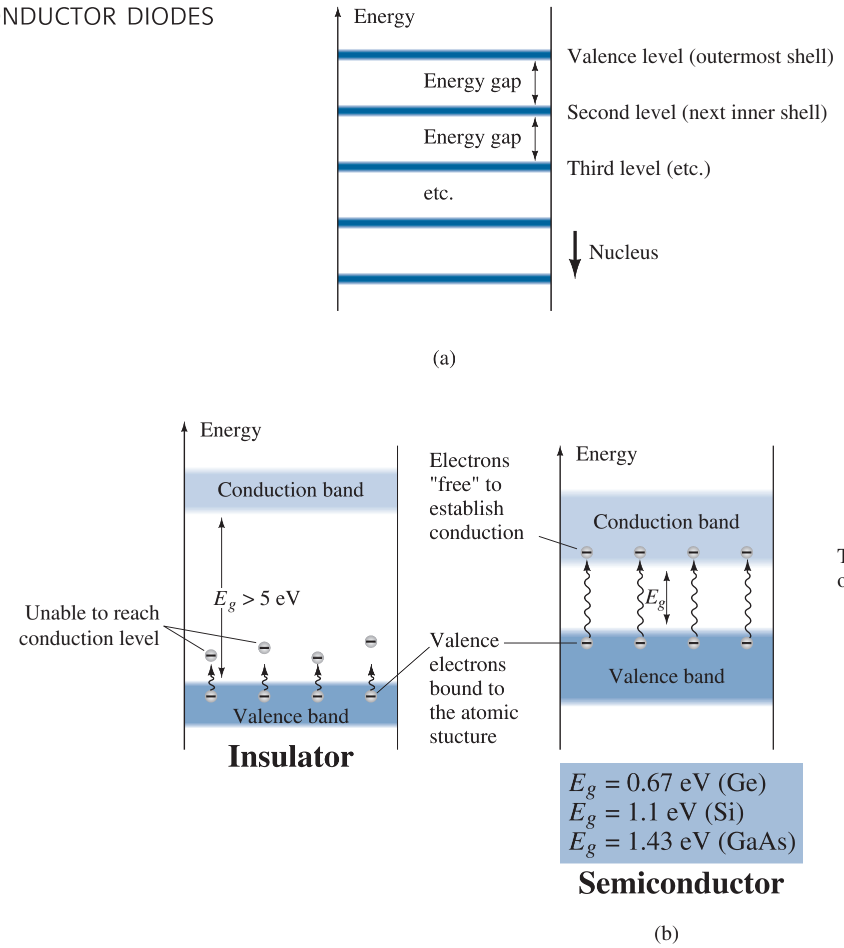


FIG. 6

Energy levels: (a) discrete levels in isolated atomic structures; (b) conduction and valence bands of an insulator, a semiconductor, and a conductor.

where carriers are not permitted. However, as the atoms of a material are brought closer together to form the crystal lattice structure, there is an interaction between atoms, which will result in the electrons of a particular shell of an atom having slightly different energy levels from electrons in the same orbit of an adjoining atom. The result is an expansion of the fixed, discrete energy levels of the valence electrons of Fig. 6a to bands as shown in Fig. 6b. In other words, the valence electrons in a silicon material can have varying energy levels as long as they fall within the band of Fig. 6b. Figure 6b clearly reveals that there is a minimum energy level associated with electrons in the conduction band and a maximum energy level of electrons bound to the valence shell of the atom. Between the two is an energy gap that the electron in the valence band must overcome to become a free carrier. That energy gap is different for Ge, Si, and GaAs; Ge has the smallest gap and GaAs the largest gap. In total, this simply means that:

An electron in the valence band of silicon must absorb more energy than one in the valence band of germanium to become a free carrier. Similarly, an electron in the valence band of gallium arsenide must gain more energy than one in silicon or germanium to enter the conduction band.

This difference in energy gap requirements reveals the sensitivity of each type of semiconductor to changes in temperature. For instance, as the temperature of a Ge sample increases, the number of electrons that can pick up thermal energy and enter the conduction band will increase quite rapidly because the energy gap is quite small. However, the number of electrons entering the conduction band for Si or GaAs would be a great deal less. This sensitivity to changes in energy level can have positive and negative effects. The design of photodetectors sensitive to light and security systems sensitive to heat would appear to be an excellent area of application for Ge devices. However, for transistor networks, where stability is a high priority, this sensitivity to temperature or light can be a detrimental factor.

The energy gap also reveals which elements are useful in the construction of light-emitting devices such as light-emitting diodes (LEDs), which will be introduced shortly. The wider the energy gap, the greater is the possibility of energy being released in the form of visible or invisible (infrared) light waves. For conductors, the overlapping of valence and conduction bands essentially results in all the additional energy picked up by the electrons being dissipated in the form of heat. Similarly, for Ge and Si, because the energy gap is so small, most of the electrons that pick up sufficient energy to leave the valence band end up in the conduction band, and the energy is dissipated in the form of heat. However, for GaAs the gap is sufficiently large to result in significant light radiation. For LEDs (Section 9) the level of doping and the materials chosen determine the resulting color.

Before we leave this subject, it is important to underscore the importance of understanding the units used for a quantity. In Fig. 6 the units of measurement are *electron volts* (eV). The unit of measure is appropriate because W (energy) $= QV$ (as derived from the defining equation for voltage: $V = W/Q$). Substituting the charge of one electron and a potential difference of 1 V results in an energy level referred to as one *electron volt*.

That is,

$$\begin{aligned} W &= QV \\ &= (1.6 \times 10^{-19}\ \text{C})(1\ \text{V}) \\ &= 1.6 \times 10^{-19}\ \text{J} \end{aligned}$$

and

$$\boxed{1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}} \qquad \textbf{(1)}$$

5 *n*-TYPE AND *p*-TYPE MATERIALS

Because Si is the material used most frequently as the base (substrate) material in the construction of solid-state electronic devices, the discussion to follow in this and the next few sections deals solely with Si semiconductors. Because Ge, Si, and GaAs share a similar covalent bonding, the discussion can easily be extended to include the use of the other materials in the manufacturing process.

As indicated earlier, the characteristics of a semiconductor material can be altered significantly by the addition of specific impurity atoms to the relatively pure semiconductor material. These impurities, although only added at 1 part in 10 million, can alter the band structure sufficiently to totally change the electrical properties of the material.

A semiconductor material that has been subjected to the doping process is called an extrinsic material.

There are two extrinsic materials of immeasureable importance to semiconductor device fabrication: *n*-type and *p*-type materials. Each is described in some detail in the following subsections.

n-Type Material

Both *n*-type and *p*-type materials are formed by adding a predetermined number of impurity atoms to a silicon base. An *n*-type material is created by introducing impurity elements that have *five* valence electrons (*pentavalent*), such as *antimony*, *arsenic*, and *phosphorus.* Each is a member of a subset group of elements in the Periodic Table of Elements referred to as Group V because each has five valence electrons. The effect of such impurity elements is indicated in Fig. 7 (using antimony as the impurity in a silicon base). Note that the four covalent bonds are still present. There is, however, an additional fifth electron due to the impurity atom, which is *unassociated* with any particular covalent bond. This remaining electron, loosely bound to its parent (antimony) atom, is relatively free to move within the newly formed *n*-type material. Since the inserted impurity atom has donated a relatively "free" electron to the structure:

Diffused impurities with five valence electrons are called donor atoms.

It is important to realize that even though a large number of free carriers have been established in the *n*-type material, it is still electrically *neutral* since ideally the number of positively charged protons in the nuclei is still equal to the number of free and orbiting negatively charged electrons in the structure.

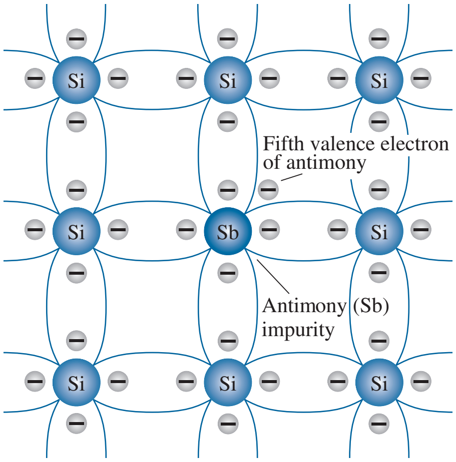


FIG. 7
Antimony impurity in n-type material.

The effect of this doping process on the relative conductivity can best be described through the use of the energy-band diagram of Fig. 8. Note that a discrete energy level (called the *donor level*) appears in the forbidden band with an E_g significantly less than that of the intrinsic material. Those free electrons due to the added impurity sit at this energy level and have less difficulty absorbing a sufficient measure of thermal energy to move into the conduction band at room temperature. The result is that at room temperature, there are a large number of carriers (electrons) in the conduction level, and the conductivity of the material increases significantly. At room temperature in an intrinsic Si material there is about one free electron for every 10^{12} atoms. If the dosage level is 1 in 10 million (10^7), the ratio $10^{12}/10^7 = 10^5$ indicates that the carrier concentration has increased by a ratio of 100,000:1.

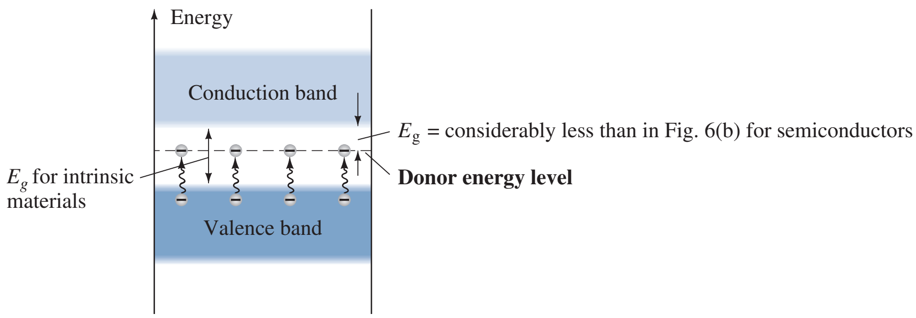


FIG. 8
Effect of donor impurities on the energy band structure.

p-Type Material

The *p*-type material is formed by doping a pure germanium or silicon crystal with impurity atoms having *three* valence electrons. The elements most frequently used for this purpose are *boron*, *gallium*, and *indium*. Each is a member of a subset group of elements in the Periodic Table of Elements referred to as Group III because each has three valence electrons. The effect of one of these elements, boron, on a base of silicon is indicated in Fig. 9.

Note that there is now an insufficient number of electrons to complete the covalent bonds of the newly formed lattice. The resulting vacancy is called a *hole* and is represented by a small circle or a plus sign, indicating the absence of a negative charge. Since the resulting vacancy will readily *accept* a free electron:

The diffused impurities with three valence electrons are called acceptor atoms.

The resulting *p*-type material is electrically neutral, for the same reasons described for the *n*-type material.

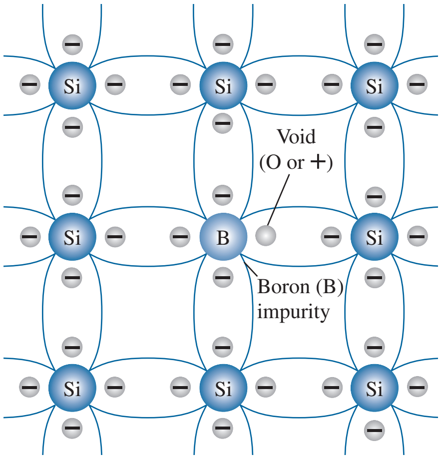


FIG. 9
Boron impurity in p-type material.

Electron versus Hole Flow

The effect of the hole on conduction is shown in Fig. 10. If a valence electron acquires sufficient kinetic energy to break its covalent bond and fills the void created by a hole, then a vacancy, or hole, will be created in the covalent bond that released the electron. There is, therefore, a transfer of holes to the left and electrons to the right, as shown in Fig. 10. The direction to be used in this text is that of *conventional flow*, which is indicated by the direction of hole flow.

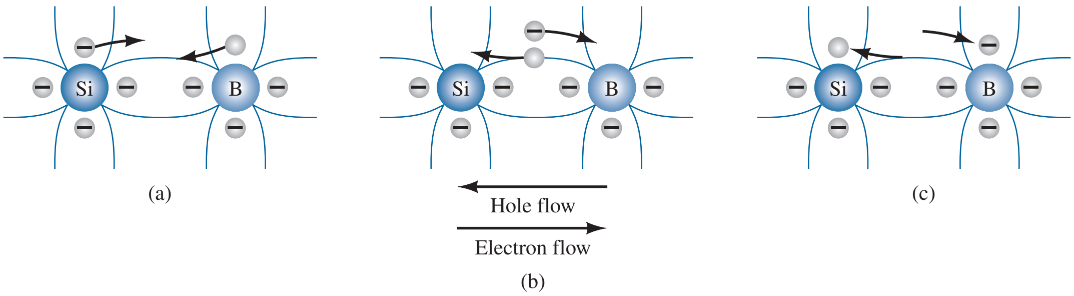


FIG. 10
Electron versus hole flow.

Majority and Minority Carriers

In the intrinsic state, the number of free electrons in Ge or Si is due only to those few electrons in the valence band that have acquired sufficient energy from thermal or light sources to break the covalent bond or to the few impurities that could not be removed. The vacancies left behind in the covalent bonding structure represent our very limited supply of holes. In an *n*-type material, the number of holes has not changed significantly from this intrinsic level. The net result, therefore, is that the number of electrons far outweighs the number of holes. For this reason:

In an n-type material (Fig. 11a) the electron is called the majority carrier and the hole the minority carrier.

For the *p*-type material the number of holes far outweighs the number of electrons, as shown in Fig. 11b. Therefore:

In a p-type material the hole is the majority carrier and the electron is the minority carrier.

When the fifth electron of a donor atom leaves the parent atom, the atom remaining acquires a net positive charge: hence the plus sign in the donor-ion representation. For similar reasons, the minus sign appears in the acceptor ion.

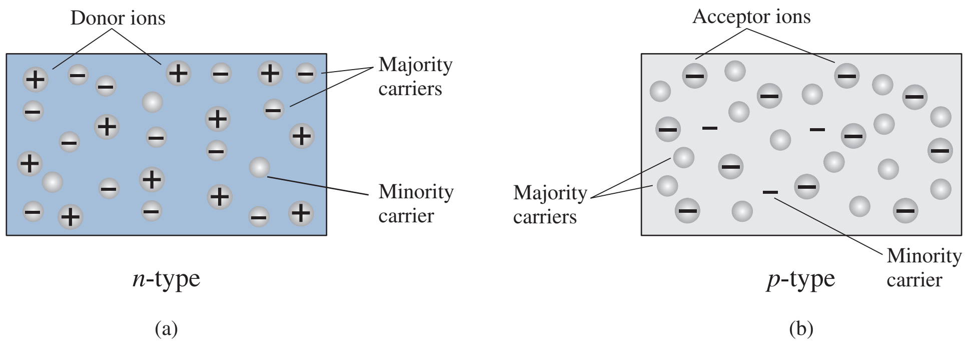


FIG. 11
(a) n-type material; (b) p-type material.

The *n*- and *p*-type materials represent the basic building blocks of semiconductor devices. We will find in the next section that the "joining" of a single *n*-type material with a *p*-type material will result in a semiconductor element of considerable importance in electronic systems.

6 SEMICONDUCTOR DIODE

Now that both *n*- and *p*-type materials are available, we can construct our first solid-state electronic device: The *semiconductor diode*, with applications too numerous to mention, is created by simply joining an *n*-type and a *p*-type material together, nothing more, just the joining of one material with a majority carrier of electrons to one with a majority carrier of holes. The basic simplicity of its construction simply reinforces the importance of the development of this solid-state era.

No Applied Bias ($V = 0$ V)

At the instant the two materials are "joined" the electrons and the holes in the region of the junction will combine, resulting in a lack of free carriers in the region near the junction, as shown in Fig. 12a. Note in Fig. 12a that the only particles displayed in this region are the positive and the negative ions remaining once the free carriers have been absorbed.

This region of uncovered positive and negative ions is called the depletion region due to the "depletion" of free carriers in the region.

If leads are connected to the ends of each material, a *two-terminal device* results, as shown in Figs. 12a and 12b. Three options then become available: *no bias*, *forward bias*, and *reverse bias*. The term *bias* refers to the application of an external voltage across the two terminals of the device to extract a response. The condition shown in Figs. 12a and 12b is the no-bias situation because there is no external voltage applied. It is simply a diode with two leads sitting isolated on a laboratory bench. In Fig. 12b the symbol for a semiconductor diode is provided to show its correspondence with the *p–n* junction. In each figure it is clear that the applied voltage is 0 V (no bias) and the resulting current is 0 A, much like an isolated resistor. The absence of a voltage across a resistor results in zero current through it. Even at this early point in the discussion it is important to note the polarity of the voltage across the diode in Fig. 12b and the direction given to the current. Those polarities will be recognized as the *defined polarities* for the semiconductor diode. If a voltage applied across the diode has the same polarity across the diode as in Fig. 12b, it will be considered a positive voltage. If the reverse, it is a negative voltage. The same standards can be applied to the defined direction of current in Fig. 12b.

Under no-bias conditions, any minority carriers (holes) in the *n*-type material that find themselves within the depletion region for any reason whatsoever will pass quickly into the *p*-type material. The closer the minority carrier is to the junction, the greater is the attraction for the layer of negative ions and the less is the opposition offered by the positive ions in the depletion region of the *n*-type material. We will conclude, therefore, for future discussions, that any minority carriers of the *n*-type material that find themselves in the depletion region will pass directly into the *p*-type material. This carrier flow is indicated at the top of Fig. 12c for the minority carriers of each material.

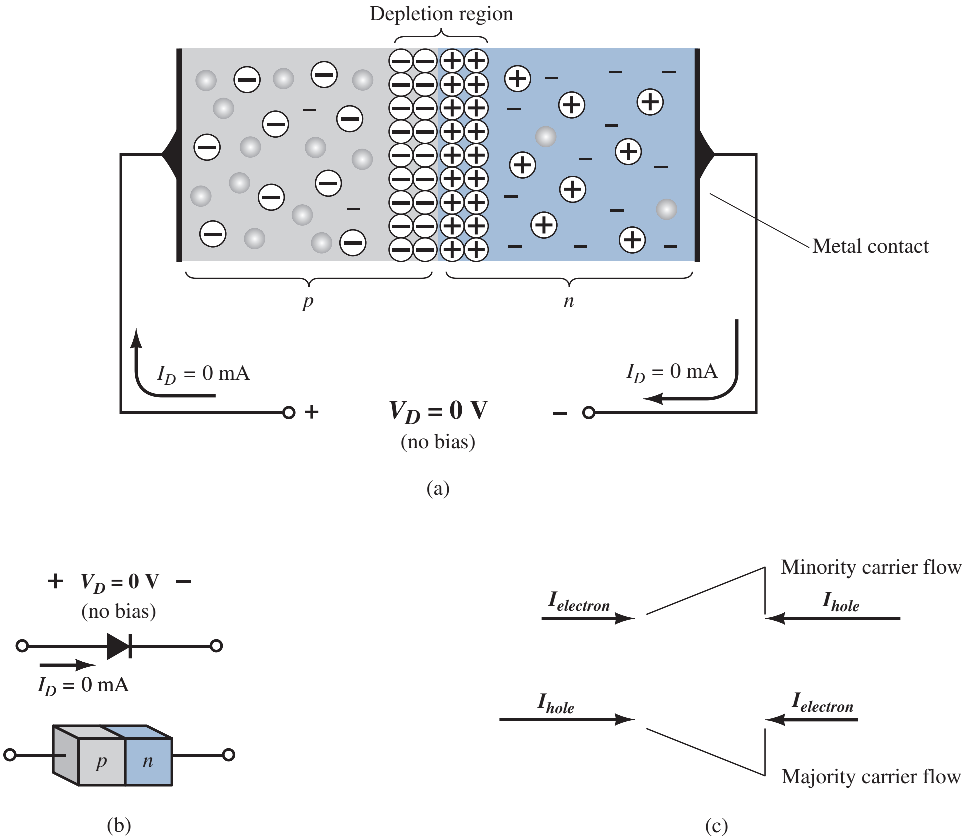


FIG. 12

A p–n junction with no external bias: (a) an internal distribution of charge; (b) a diode symbol, with the defined polarity and the current direction; (c) demonstration that the net carrier flow is zero at the external terminal of the device when $V_D = 0$ V.

The majority carriers (electrons) of the *n*-type material must overcome the attractive forces of the layer of positive ions in the *n*-type material and the shield of negative ions in the *p*-type material to migrate into the area beyond the depletion region of the *p*-type material. However, the number of majority carriers is so large in the *n*-type material that there will invariably be a small number of majority carriers with sufficient kinetic energy to pass through the depletion region into the *p*-type material. Again, the same type of discussion can be applied to the majority carriers (holes) of the *p*-type material. The resulting flow due to the majority carriers is shown at the bottom of Fig. 12c.

A close examination of Fig. 12c will reveal that the relative magnitudes of the flow vectors are such that the net flow in either direction is zero. This cancellation of vectors for each type of carrier flow is indicated by the crossed lines. The length of the vector representing hole flow is drawn longer than that of electron flow to demonstrate that the two magnitudes need not be the same for cancellation and that the doping levels for each material may result in an unequal carrier flow of holes and electrons. In summary, therefore:

In the absence of an applied bias across a semiconductor diode, the net flow of charge in one direction is zero.

In other words, the current under no-bias conditions is zero, as shown in Figs. 12a and 12b.

Reverse-Bias Condition ($V_D < 0$ V)

If an external potential of *V* volts is applied across the *p–n* junction such that the positive terminal is connected to the *n*-type material and the negative terminal is connected to the *p*-type material as shown in Fig. 13, the number of uncovered positive ions in the depletion region of the *n*-type material will increase due to the large number of free electrons drawn to the positive potential of the applied voltage. For similar reasons, the number of uncovered negative ions will increase in the *p*-type material. The net effect, therefore, is a

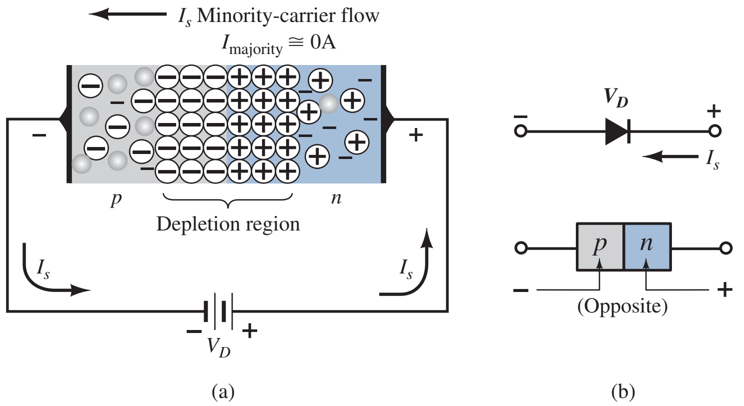


FIG. 13

Reverse-biased p–n junction: (a) internal distribution of charge under reverse-bias conditions; (b) reverse-bias polarity and direction of reverse saturation current.

widening of the depletion region. This widening of the depletion region will establish too great a barrier for the majority carriers to overcome, effectively reducing the majority carrier flow to zero, as shown in Fig. 13a.

The number of minority carriers, however, entering the depletion region will not change, resulting in minority-carrier flow vectors of the same magnitude indicated in Fig. 12c with no applied voltage.

The current that exists under reverse-bias conditions is called the reverse saturation current and is represented by I_s.

The reverse saturation current is seldom more than a few microamperes and typically in nA, except for high-power devices. The term *saturation* comes from the fact that it reaches its maximum level quickly and does not change significantly with increases in the reverse-bias potential, as shown on the diode characteristics of Fig. 15 for $V_D < 0$ V. The reverse-biased conditions are depicted in Fig. 13b for the diode symbol and *p–n* junction. Note, in particular, that the direction of I_s is against the arrow of the symbol. Note also that the negative side of the applied voltage is connected to the *p*-type material and the positive side to the *n*-type material, the difference in underlined letters for each region revealing a reverse-bias condition.

Forward-Bias Condition ($V_D > 0$ V)

A *forward-bias* or "on" condition is established by applying the positive potential to the *p*-type material and the negative potential to the *n*-type material as shown in Fig. 14.

The application of a forward-bias potential V_D will "pressure" electrons in the *n*-type material and holes in the *p*-type material to recombine with the ions near the boundary and reduce the width of the depletion region as shown in Fig. 14a. The resulting minority-carrier flow

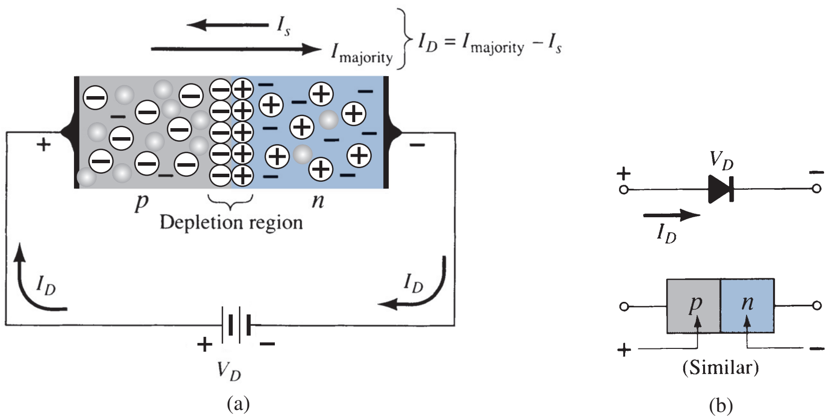


FIG. 14

Forward-biased p–n junction: (a) internal distribution of charge under forward-bias conditions; (b) forward-bias polarity and direction of resulting current.

of electrons from the *p*-type material to the *n*-type material (and of holes from the *n*-type material to the *p*-type material) has not changed in magnitude (since the conduction level is controlled primarily by the limited number of impurities in the material), but the reduction in the width of the depletion region has resulted in a heavy majority flow across the junction. An electron of the *n*-type material now "sees" a reduced barrier at the junction due to the reduced depletion region and a strong attraction for the positive potential applied to the *p*-type material. As the applied bias increases in magnitude, the depletion region will continue to decrease in width until a flood of electrons can pass through the junction, resulting in an exponential rise in current as shown in the forward-bias region of the characteristics of Fig. 15. Note that the vertical scale of Fig. 15 is measured in milliamperes (although some semiconductor diodes have a vertical scale measured in amperes), and the horizontal scale in the forward-bias region has a maximum of 1 V. Typically, therefore, the voltage across a forward-biased diode will be less than 1 V. Note also how quickly the current rises beyond the knee of the curve.

It can be demonstrated through the use of solid-state physics that the general characteristics of a semiconductor diode can be defined by the following equation, referred to as Shockley's equation, for the forward- and reverse-bias regions:

$$\boxed{I_D = I_s(e^{V_D/nV_T} - 1)} \quad \text{(A)} \tag{2}$$

where I_s is the reverse saturation current
V_D is the applied forward-bias voltage across the diode
n is an ideality factor, which is a function of the operating conditions and physical construction; it has a range between 1 and 2 depending on a wide variety of factors ($n = 1$ will be assumed throughout this text unless otherwise noted).

The voltage V_T in Eq. (1) is called the *thermal voltage* and is determined by

$$\boxed{V_T = \frac{kT_K}{q}} \quad \text{(V)} \tag{3}$$

where k is Boltzmann's constant $= 1.38 \times 10^{-23}$ J/K
T_K is the absolute temperature in kelvins $= 273 +$ the temperature in °C
q is the magnitude of electronic charge $= 1.6 \times 10^{-19}$ C

EXAMPLE 1 At a temperature of 27°C (common temperature for components in an enclosed operating system), determine the thermal voltage V_T.

Solution: Substituting into Eq. (3), we obtain

$$T = 273 + {}^\circ\text{C} = 273 + 27 = 300\text{ K}$$
$$V_T = \frac{kT_K}{q} = \frac{(1.38 \times 10^{-23}\text{ J/K})(30\text{ K})}{1.6 \times 10^{-19}\text{ C}}$$
$$= 25.875\text{ mV} \cong 26\text{ mV}$$

The thermal voltage will become an important parameter in the analysis to follow in this chapter.

Initially, Eq. (2) with all its defined quantities may appear somewhat complex. However, it will not be used extensively in the analysis to follow. It is simply important at this point to understand the source of the diode characteristics and which factors affect its shape.

A plot of Eq. (2) with $I_s = 10$ pA is provided in Fig. 15 as the dashed line. If we expand Eq. (2) into the following form, the contributing component for each region of Fig. 15 can be described with increased clarity:

$$I_D = I_s e^{V_D/nV_T} - I_s$$

For positive values of V_D the first term of the above equation will grow very quickly and totally overpower the effect of the second term. The result is the following equation, which only has positive values and takes on the exponential format e^x appearing in Fig. 16:

$$I_D \cong I_s e^{V_D/nV_T} \qquad (V_D \text{ positive})$$

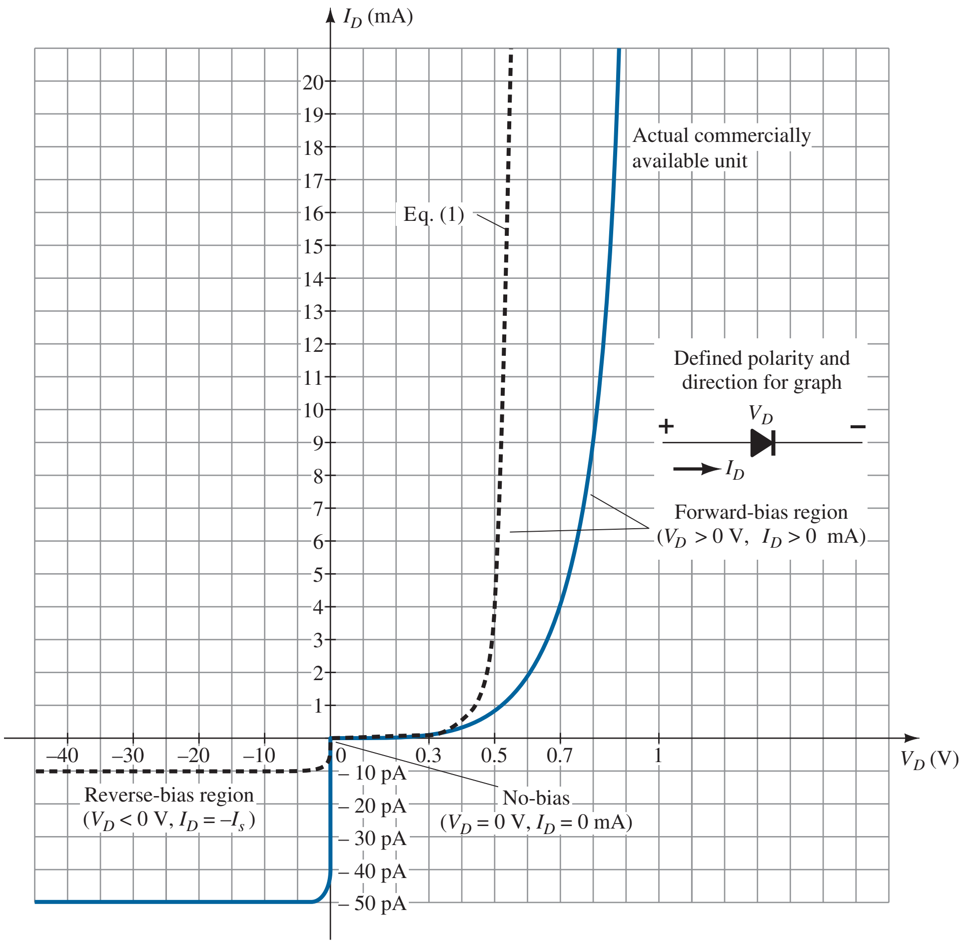


FIG. 15
Silicon semiconductor diode characteristics.

The exponential curve of Fig. 16 increases very rapidly with increasing values of x. At $x = 0$, $e^0 = 1$, whereas at $x = 5$, it jumps to greater than 148. If we continued to $x = 10$, the curve jumps to greater than 22,000. Clearly, therefore, as the value of x increases, the curve becomes almost vertical, an important conclusion to keep in mind when we examine the change in current with increasing values of applied voltage.

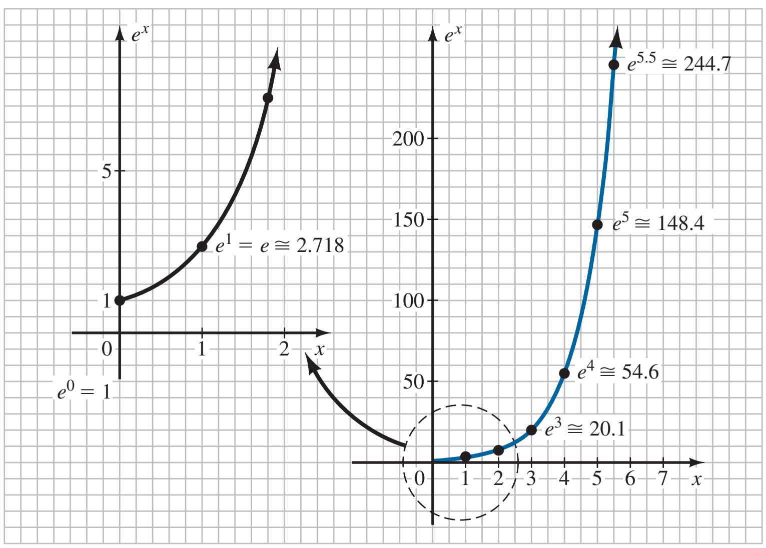


FIG. 16
Plot of e^x.

For negative values of V_D the exponential term drops very quickly below the level of I, and the resulting equation for I_D is simply

$$I_D \cong -I_s \qquad (V_D \text{ negative})$$

Note in Fig. 15 that for negative values of V_D the current is essentially horizontal at the level of $-I_s$.

At $V = 0$ V, Eq. (2) becomes

$$I_D = I_s(e^0 - 1) = I_s(1 - 1) = 0 \text{ mA}$$

as confirmed by Fig. 15.

The sharp change in direction of the curve at $V_D = 0$ V is simply due to the change in current scales from above the axis to below the axis. Note that above the axis the scale is in milliamperes (mA), whereas below the axis it is in picoamperes (pA).

Theoretically, with all things perfect, the characteristics of a silicon diode should appear as shown by the dashed line of Fig. 15. However, commercially available silicon diodes deviate from the ideal for a variety of reasons including the internal "body" resistance and the external "contact" resistance of a diode. Each contributes to an additional voltage at the same current level, as determined by Ohm's law, causing the shift to the right witnessed in Fig. 15.

The change in current scales between the upper and lower regions of the graph was noted earlier. For the voltage V_D there is also a measurable change in scale between the right-hand region of the graph and the left-hand region. For positive values of V_D the scale is in tenths of volts, and for the negative region it is in tens of volts.

It is important to note in Fig. 14b how:

The defined direction of conventional current for the positive voltage region matches the arrowhead in the diode symbol.

This will always be the case for a forward-biased diode. It may also help to note that the forward-bias condition is established when the bar representing the negative side of the applied voltage matches the side of the symbol with the vertical bar.

Going back a step further by looking at Fig. 14b, we find a forward-bias condition is established across a *p–n* junction when the positive side of the applied voltage is applied to the *p*-type material (noting the correspondence in the letter *p*) and the negative side of the applied voltage is applied to the *n*-type material (noting the same correspondence).

It is particularly interesting to note that the reverse saturation current of the commercial unit is significantly larger than that of I_s in Shockley's equation. In fact,

The actual reverse saturation current of a commercially available diode will normally be measurably larger than that appearing as the reverse saturation current in Shockley's equation.

This increase in level is due to a wide range of factors that include

- **leakage currents**
- **generation of carriers in the depletion region**
- **higher doping levels** that result in increased levels of reverse current
- **sensitivity to the intrinsic level of carriers** in the component materials by a squared factor—double the intrinsic level, and the contribution to the reverse current could increase by a factor of four.
- **a direct relationship with the junction area**—double the area of the junction, and the contribution to the reverse current could double. High-power devices that have larger junction areas typically have much higher levels of reverse current.
- **temperature sensitivity**—for every 5°C increase in current, the level of reverse saturation current in Eq. 2 will double, whereas a 10°C increase in current will result in doubling of the actual reverse current of a diode.

Note in the above the use of the terms reverse saturation current and reverse current. The former is simply due to the physics of the situation, whereas the latter includes all the other possible effects that can increase the level of current.

We will find in the discussions to follow that the ideal situation is for I_s to be 0 A in the reverse-bias region. The fact that it is typically in the range of 0.01 pA to 10 pA today as compared to 0.1 μA to 1 μA a few decades ago is a credit to the manufacturing industry. Comparing the common value of 1 nA to the 1-μA level of years past shows an improvement factor of 100,000.

Breakdown Region

Even though the scale of Fig. 15 is in tens of volts in the negative region, there is a point where the application of too negative a voltage with the reverse polarity will result in a sharp change in the characteristics, as shown in Fig. 17. The current increases at a very rapid rate in a direction opposite to that of the positive voltage region. The reverse-bias potential that results in this dramatic change in characteristics is called the *breakdown potential* and is given the label V_{BV}.

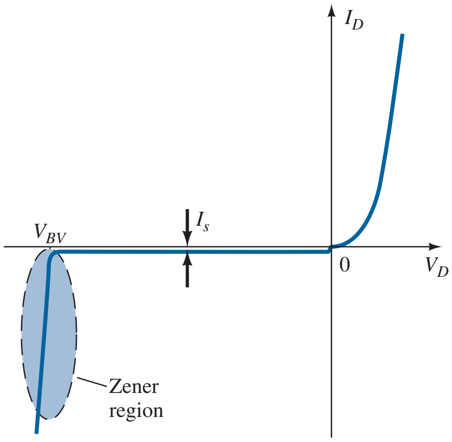


FIG. 17
Breakdown region.

As the voltage across the diode increases in the reverse-bias region, the velocity of the minority carriers responsible for the reverse saturation current I_s will also increase. Eventually, their velocity and associated kinetic energy ($W_K = \frac{1}{2}mv^2$) will be sufficient to release additional carriers through collisions with otherwise stable atomic structures. That is, an *ionization* process will result whereby valence electrons absorb sufficient energy to leave the parent atom. These additional carriers can then aid the ionization process to the point where a high *avalanche* current is established and the *avalanche breakdown* region determined.

The avalanche region (V_{BV}) can be brought closer to the vertical axis by increasing the doping levels in the *p*- and *n*-type materials. However, as V_{BV} decreases to very low levels, such as -5 V, another mechanism, called *Zener breakdown*, will contribute to the sharp change in the characteristic. It occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and "generate" carriers. Although the Zener breakdown mechanism is a significant contributor only at lower levels of V_{BV}, this sharp change in the characteristic at any level is called the *Zener region*, and diodes employing this unique portion of the characteristic of a *p–n* junction are called *Zener diodes*. They are described in detail in Section 15.

The breakdown region of the semiconductor diode described must be avoided if the response of a system is not to be completely altered by the sharp change in characteristics in this reverse-voltage region.

The maximum reverse-bias potential that can be applied before entering the breakdown region is called the peak inverse voltage (referred to simply as the PIV rating) or the peak reverse voltage (denoted the PRV rating).

If an application requires a PIV rating greater than that of a single unit, a number of diodes of the same characteristics can be connected in series. Diodes are also connected in parallel to increase the current-carrying capacity.

In general, the breakdown voltage of GaAs diodes is about 10% higher those for silicon diodes but after 200% higher than levels for Ge diodes.

Ge, Si, and GaAs

The discussion thus far has solely used Si as the base semiconductor material. It is now important to compare it to the other two materials of importance: GaAs and Ge. A plot comparing the characteristics of Si, GaAs, and Ge diodes is provided in Fig. 18. The curves are not

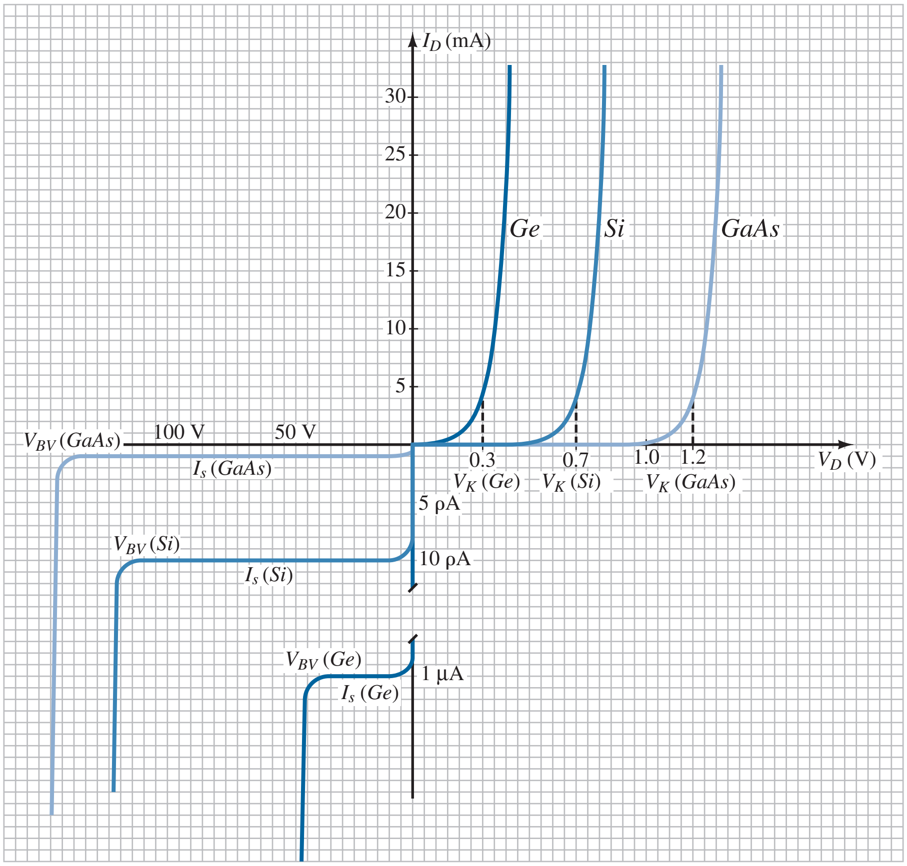


FIG. 18
Comparison of Ge, Si, and GaAs commercial diodes.

simply plots of Eq. 2 but the actual response of commercially available units. The total reverse current is shown and not simply the reverse saturation current. It is immediately obvious that the point of vertical rise in the characteristics is different for each material, although the general shape of each characteristic is quite similar. Germanium is closest to the vertical axis and GaAs is the most distant. As noted on the curves, the center of the knee (hence the *K* is the notation V_K) of the curve is about 0.3 V for Ge, 0.7 V for Si, and 1.2 V for GaAs (see Table 3).

The shape of the curve in the reverse-bias region is also quite similar for each material, but notice the measurable difference in the magnitudes of the typical reverse saturation currents. For GaAs, the reverse saturation current is typically about 1 pA, compared to 10 pA for Si and 1 μA for Ge, a significant difference in levels.

Also note the relative magnitudes of the reverse breakdown voltages for each material. GaAs typically has maximum breakdown levels that exceed those of Si devices of the same power level by about 10%, with both having breakdown voltages that typically extend between 50 V and 1 kV. There are Si power diodes with breakdown voltages as high as 20 kV. Germanium typically has breakdown voltages of less than 100 V, with maximums around 400 V. The curves of Fig. 18 are simply designed to reflect relative breakdown voltages for the three materials. When one considers the levels of reverse saturation currents and breakdown voltages, Ge certainly sticks out as having the least desirable characteristics.

A factor not appearing in Fig. 18 is the operating speed for each material—an important factor in today's market. For each material, the electron mobility factor is provided in Table 4. It provides an indication of how fast the carriers can progress through the material and therefore the operating speed of any device made using the materials. Quite obviously, GaAs stands out, with a mobility factor more than five times that of silicon and twice that of germanium. The result is that GaAs and Ge are often used in high-speed applications. However, through proper design, careful control of doping levels, and so on, silicon is also found in systems operating in the gigahertz range. Research today is also looking at compounds in groups III–V that have even higher mobility factors to ensure that industry can meet the demands of future high-speed requirements.

TABLE 3
Knee Voltages V_K

Semiconductor	V_K(V)
Ge	0.3
Si	0.7
GaAs	1.2

TABLE 4
Electron Mobility μ_n

Semiconductor	μ_n(cm^2/V·s)
Ge	3900
Si	1500
GaAs	8500

EXAMPLE 2 Using the curves of Fig 18:

a. Determine the voltage across each diode at a current of 1 mA.
b. Repeat for a current of 4 mA.
c. Repeat for a current of 30 mA.
d. Determine the average value of the diode voltage for the range of currents listed above.
e. How do the average values compare to the knee voltages listed in Table 3?

Solution:

a. $V_D(\text{Ge}) = 0.2\text{ V}$, $V_D(\text{Si}) = 0.6\text{ V}$, $V_D\,(\text{GaAs}) = 1.1\text{ V}$
b. $V_D(\text{Ge}) = 0.3\text{ V}$, $V_D(\text{Si}) = 0.7\text{ V}$, $V_D\,(\text{GaAs}) = 1.2\text{ V}$
c. $V_D(\text{Ge}) = 0.42\text{ V}$, $V_D(\text{Si}) = 0.82\text{ V}$, $V_D\,(\text{GaAs}) = 1.33\text{ V}$
d. Ge: $V_{av} = (0.2\text{ V} + 0.3\text{ V} + 0.42\text{ V})/3 = 0.307\text{ V}$
   Si: $V_{av} = (0.6\text{ V} + 0.7\text{ V} + 0.82\text{ V})/3 = 0.707\text{ V}$
   GaAs: $V_{av} = (1.1\text{ V} + 1.2\text{ V} + 1.33\text{ V})/3 = 1.21\text{ V}$
e. Very close correspondence. Ge: 0.307 V vs. 0.3, V, Si: 0.707 V vs. 0.7 V, GaAs: 1.21 V vs. 1.2 V.

Temperature Effects

Temperature can have a marked effect on the characteristics of a semiconductor diode, as demonstrated by the characteristics of a silicon diode shown in Fig. 19:

In the forward-bias region the characteristics of a silicon diode shift to the left at a rate of 2.5 mV per centigrade degree increase in temperature.

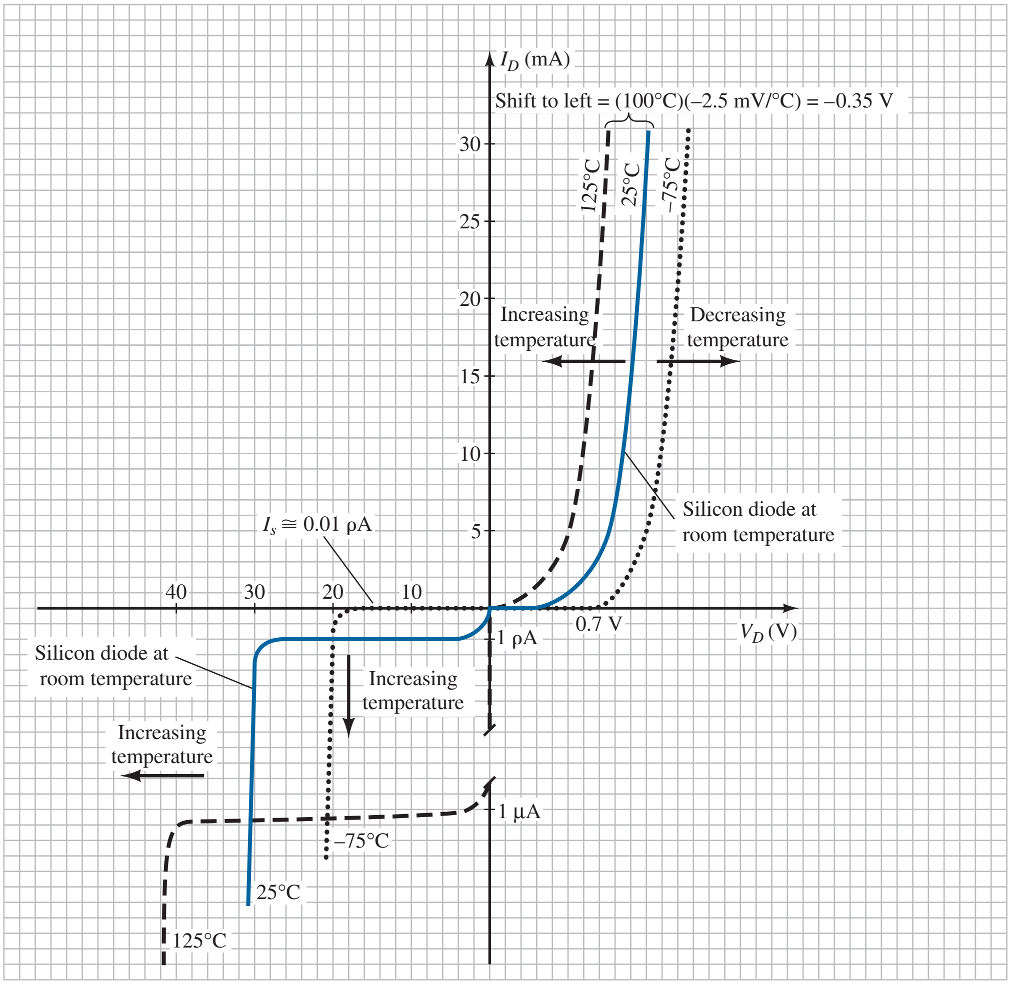


FIG. 19
Variation in Si diode characteristics with temperature change.

An increase from room temperature (20°C) to 100°C (the boiling point of water) results in a drop of 80(2.5 mV) = 200 mV, or 0.2 V, which is significant on a graph scaled in tenths of volts. A decrease in temperature has the reverse effect, as also shown in the figure:

In the reverse-bias region the reverse current of a silicon diode doubles for every 10°C rise in temperature.

For a change from 20°C to 100°C, the level of I_s increases from 10 nA to a value of 2.56 μA, which is a significant, 256-fold increase. Continuing to 200°C would result in a monstrous reverse saturation current of 2.62 mA. For high-temperature applications one would therefore look for Si diodes with room-temperature I_s closer to 10 pA, a level commonly available today, which would limit the current to 2.62 μA. It is indeed fortunate that both Si and GaAs have relatively small reverse saturation currents at room temperature. GaAs devices are available that work very well in the −200°C to +200°C temperature range, with some having maximum temperatures approaching 400°C. Consider, for a moment, how huge the reverse saturation current would be if we started with a Ge diode with a saturation current of 1 μA and applied the same doubling factor.

Finally, it is important to note from Fig. 19 that:

The reverse breakdown voltage of a semiconductor diode will increase or decrease with temperature.

However, if the initial breakdown voltage is less than 5 V, the breakdown voltage may actually decrease with temperature. The sensitivity of the breakdown potential to changes of temperature will be examined in more detail in Section 15.

Summary

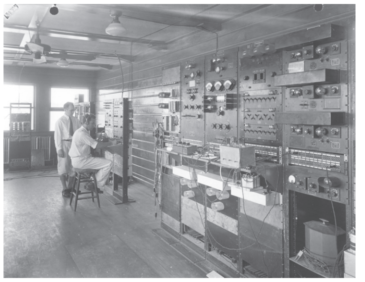
A great deal has been introduced in the foregoing paragraphs about the construction of a semiconductor diode and the materials employed. The characteristics have now been presented and the important differences between the response of the materials discussed. It is now time to compare the *p–n* junction response to the desired response and reveal the primary functions of a semiconductor diode.

Table 5 provides a synopsis of material regarding the three most frequently used semiconductor materials. Figure 20 includes a short biography of the first research scientist to discover the *p–n* junction in a semiconductor material.

TABLE 5

The Current Commercial Use of Ge, Si, and GaAs

Ge:	Germanium is in limited production due to its temperature sensitivity and high reverse saturation current. It is still commercially available but is limited to some high-speed applications (due to a relatively high mobility factor) and applications that use its sensitivity to light and heat such as photodetectors and security systems.
Si:	Without question the semiconductor used most frequently for the full range of electronic devices. It has the advantage of being readily available at low cost and has relatively low reverse saturation currents, good temperature characteristics, and excellent breakdown voltage levels. It also benefits from decades of enormous attention to the design of large-scale integrated circuits and processing technology.
GaAs:	Since the early 1990s the interest in GaAs has grown in leaps and bounds, and it will eventually take a good share of the development from silicon devices, especially in very large scale integrated circuits. Its high-speed characteristics are in more demand every day, with the added features of low reverse saturation currents, excellent temperature sensitivities, and high breakdown voltages. More than 80% of its applications are in optoelectronics with the development of light-emitting diodes, solar cells, and other photodetector devices, but that will probably change dramatically as its manufacturing costs drop and its use in integrated circuit design continues to grow; perhaps the semiconductor material of the future.



Russell Ohl (1898–1987)

American (Allentown, PA; Holmdel, NJ; Vista, CA) Army Signal Corps, University of Colorado, Westinghouse, AT&T, Bell Labs Fellow, Institute of Radio Engineers—1955 (Courtesy of AT&T Archives History Center.)

Although vacuum tubes were used in all forms of communication in the 1930s, Russell Ohl was determined to demonstrate that the future of the field was defined by semiconductor crystals. Germanium was not immediately available for his research, so he turned to silicon, and found a way to raise its level of purity to 99.8%, for which he received a patent. The actual discovery of the *p–n* junction, as often happens in scientific research, was the result of a set of circumstances that were not planned. On February 23, 1940, Ohl found that a silicon crystal with a crack down the middle would produce a significant rise in current when placed near a source of light. This discovery led to further research, which revealed that the purity levels on each side of the crack were different and that a barrier was formed at the junction that allowed the passage of current in only one direction—the first solid-state diode had been identified and explained. In addition, this sensitivity to light was the beginning of the development of solar cells. The results were quite instrumental in the development of the transistor in 1945 by three individuals also working at Bell Labs.

FIG. 20

7 IDEAL VERSUS PRACTICAL

In the previous section we found that a *p–n* junction will permit a generous flow of charge when forward-biased and a very small level of current when reverse-biased. Both conditions are reviewed in Fig. 21, with the heavy current vector in Fig. 21a matching the direction of the arrow in the diode symbol and the significantly smaller vector in the opposite direction in Fig. 21b representing the reverse saturation current.

An analogy often used to describe the behavior of a semiconductor diode is a mechanical switch. In Fig. 21a the diode is acting like a closed switch permitting a generous flow of charge in the direction indicated. In Fig. 21b the level of current is so small in most cases that it can be approximated as 0 A and represented by an open switch.

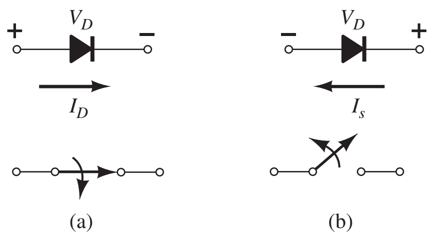


FIG. 21
Ideal semiconductor diode: (a) forward-biased; (b) reverse-biased.

In other words:

The semiconductor diode behaves in a manner similar to a mechanical switch in that it can control whether current will flow between its two terminals.

However, it is important to also be aware that:

The semiconductor diode is different from a mechanical switch in the sense that when the switch is closed it will only permit current to flow in one direction.

Ideally, if the semiconductor diode is to behave like a closed switch in the forward-bias region, the resistance of the diode should be 0 Ω. In the reverse-bias region its resistance should be ∞Ω to represent the open-circuit equivalent. Such levels of resistance in the forward- and reverse-bias regions result in the characteristics of Fig. 22.

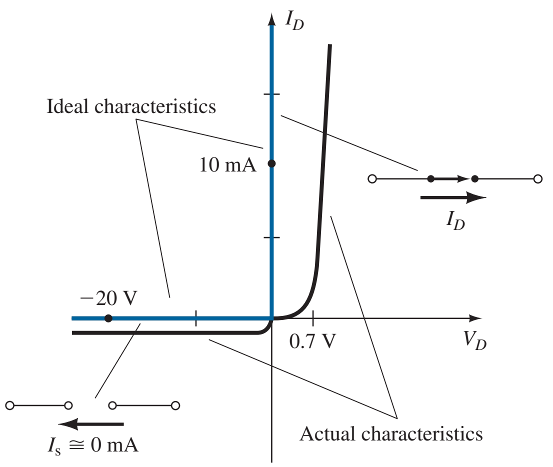


FIG. 22
Ideal versus actual semiconductor characteristics.

The characteristics have been superimposed to compare the ideal Si diode to a real-world Si diode. First impressions might suggest that the commercial unit is a poor impression of the ideal switch. However, when one considers that the only major difference is that the commercial diode rises at a level of 0.7 V rather than 0 V, there are a number of similarities between the two plots.

When a switch is closed the resistance between the contacts is assumed to be 0 Ω. At the plot point chosen on the vertical axis the diode current is 5 mA and the voltage across the diode is 0 V. Substituting into Ohm's law results in

$$R_F = \frac{V_D}{I_D} = \frac{0\text{ V}}{5\text{ mA}} = \mathbf{0\ \Omega} \qquad \text{(short-circuit equivalent)}$$

In fact:

At any current level on the vertical line, the voltage across the ideal diode is 0 V and the resistance is 0 Ω.

For the horizontal section, if we again apply Ohm's law, we find

$$R_R = \frac{V_D}{I_D} = \frac{20\text{ V}}{0\text{ mA}} \cong \infty\,\Omega \qquad \text{(open-circuit equivalent)}$$

Again:

Because the current is 0 mA anywhere on the horizontal line, the resistance is considered to be infinite ohms (an open-circuit) at any point on the axis.

Due to the shape and the location of the curve for the commercial unit in the forward-bias region there will be a resistance associated with the diode that is greater than 0 Ω. However, if that resistance is small enough compared to other resistors of the network in series with the diode, it is often a good approximation to simply assume the resistance of the commercial unit is 0 Ω. In the reverse-bias region, if we assume the reverse saturation current is so small it can be approximated as 0 mA, we have the same open-circuit equivalence provided by the open switch.

The result, therefore, is that there are sufficient similarities between the ideal switch and the semiconductor diode to make it an effective electronic device. In the next section the various resistance levels of importance are determined for use in the chapter "Diode Applications", where the response of diodes in an actual network is examined.

8 RESISTANCE LEVELS

As the operating point of a diode moves from one region to another the resistance of the diode will also change due to the nonlinear shape of the characteristic curve. It will be demonstrated in the next few paragraphs that the type of applied voltage or signal will define the resistance level of interest. Three different levels will be introduced in this section, which will appear again as we examine other devices. It is therefore paramount that their determination be clearly understood.

DC or Static Resistance

The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that will not change with time. The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D as shown in Fig. 23 and applying the following equation:

$$\boxed{R_D = \frac{V_D}{I_D}} \qquad \textbf{(4)}$$

The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics. The resistance levels in the reverse-bias region will naturally be quite high. Since ohmmeters typically employ a relatively constant-current source, the resistance determined will be at a preset current level (typically, a few milliamperes).

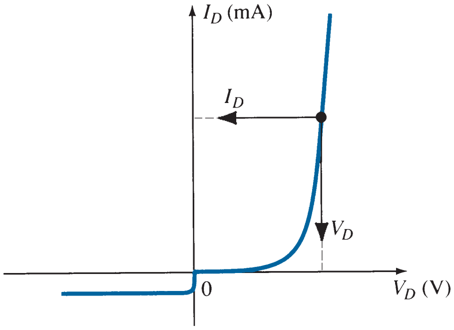


FIG. 23
Determining the dc resistance of a diode at a particular operating point.

In general, therefore, the higher the current through a diode, the lower is the dc resistance level.

Typically, the dc resistance of a diode in the active (most utilized) will range from about 10 Ω to 80 Ω.

EXAMPLE 3 Determine the dc resistance levels for the diode of Fig. 24 at

a. $I_D = 2$ mA (low level)
b. $I_D = 20$ mA (high level)
c. $V_D = -10$ V (reverse-biased)

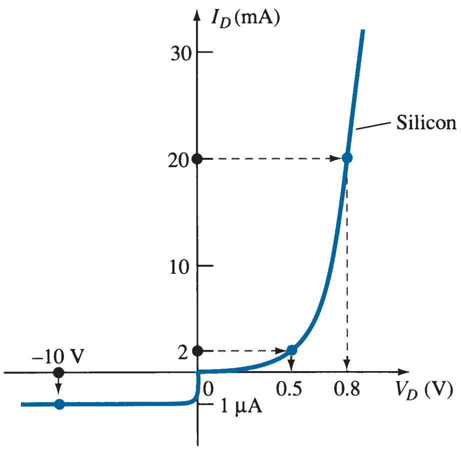


FIG. 24
Example 3.

Solution:

a. At $I_D = 2$ mA, $V_D = 0.5$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = \mathbf{250\ \Omega}$$

b. At $I_D = 20$ mA, $V_D = 0.8$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.8\text{ V}}{20\text{ mA}} = \mathbf{40\ \Omega}$$

c. At $V_D = -10$ V, $I_D = -I_s = -1\ \mu$A (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{10\text{ V}}{1\ \mu\text{A}} = \mathbf{10\ M\Omega}$$

clearly supporting some of the earlier comments regarding the dc resistance levels of a diode.

AC or Dynamic Resistance

Eq. (4) and Example 3 reveal that

the dc resistance of a diode is independent of the shape of the characteristic in the region surrounding the point of interest.

If a sinusoidal rather than a dc input is applied, the situation will change completely. The varying input will move the instantaneous operating point up and down a region of the characteristics and thus defines a specific change in current and voltage as shown in Fig. 25. With no applied varying signal, the point of operation would be the Q-point appearing on Fig. 25, determined by the applied dc levels. The designation *Q-point* is derived from the word *quiescent*, which means "still or unvarying."

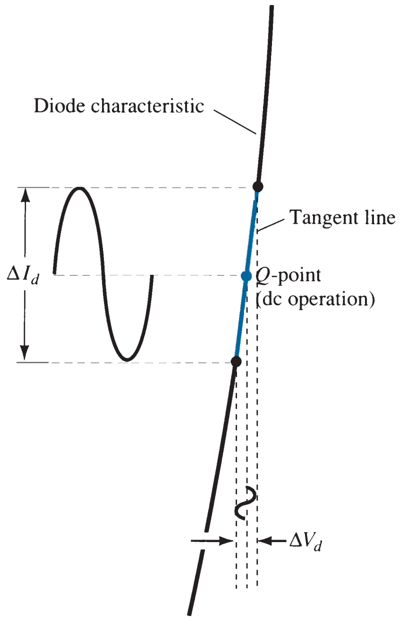


FIG. 25
Defining the dynamic or ac resistance.

A straight line drawn tangent to the curve through the Q-point as shown in Fig. 26 will define a particular change in voltage and current that can be used to determine the *ac* or *dynamic* resistance for this region of the diode characteristics. An effort should be made to keep the change in voltage and current as small as possible and equidistant to either side of the Q-point. In equation form,

$$\boxed{r_d = \frac{\Delta V_d}{\Delta I_d}} \qquad \textbf{(5)}$$

where Δ signifies a finite change in the quantity.

The steeper the slope, the lower is the value of ΔV_d for the same change in ΔI_d and the lower is the resistance. The ac resistance in the vertical-rise region of the characteristic is therefore quite small, whereas the ac resistance is much higher at low current levels.

In general, therefore, the lower the Q-point of operation (smaller current or lower voltage), the higher is the ac resistance.

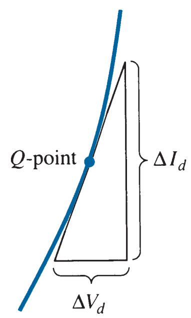


FIG. 26
Determining the ac resistance at a Q-point.

EXAMPLE 4 For the characteristics of Fig. 27:

a. Determine the ac resistance at $I_D = 2$ mA.
b. Determine the ac resistance at $I_D = 25$ mA.
c. Compare the results of parts (a) and (b) to the dc resistances at each current level.

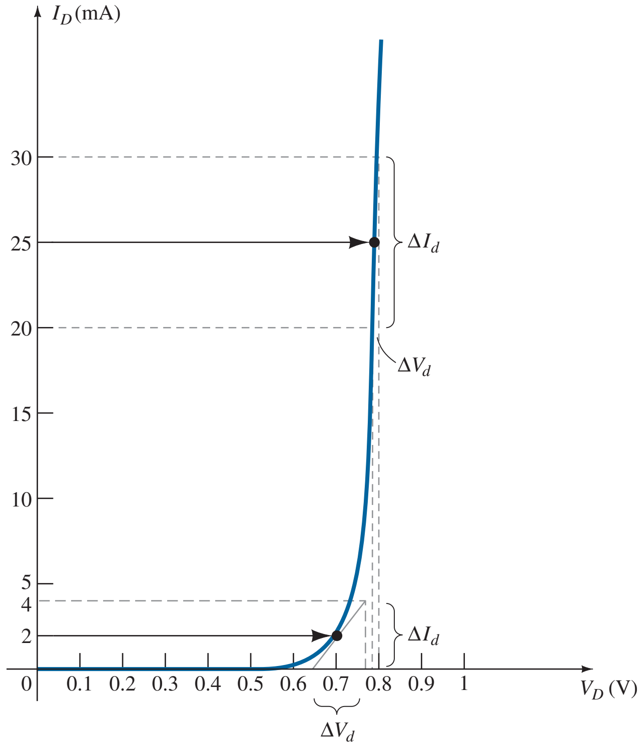


FIG. 27
Example 4.

Solution:

a. For $I_D = 2$ mA, the tangent line at $I_D = 2$ mA was drawn as shown in Fig. 27 and a swing of 2 mA above and below the specified diode current was chosen. At $I_D = 4$ mA, $V_D = 0.76$ V, and at $I_D = 0$ mA, $V_D = 0.65$ V. The resulting changes in current and voltage are, respectively,

$$\Delta I_d = 4 \text{ mA} - 0 \text{ mA} = 4 \text{ mA}$$

and
$$\Delta V_d = 0.76 \text{ V} - 0.65 \text{ V} = 0.11 \text{ V}$$

and the ac resistance is

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.11 \text{ V}}{4 \text{ mA}} = \mathbf{27.5\ \Omega}$$

b. For $I_D = 25$ mA, the tangent line at $I_D = 25$ mA was drawn as shown in Fig. 27 and a swing of 5 mA above and below the specified diode current was chosen. At $I_D = 30$ mA, $V_D = 0.8$ V, and at $I_D = 20$ mA, $V_D = 0.78$ V. The resulting changes in current and voltage are, respectively,

$$\Delta I_d = 30 \text{ mA} - 20 \text{ mA} = 10 \text{ mA}$$

and
$$\Delta V_d = 0.8 \text{ V} - 0.78 \text{ V} = 0.02 \text{ V}$$

and the ac resistance is

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.02 \text{ V}}{10 \text{ mA}} = \mathbf{2\ \Omega}$$

c. For $I_D = 2$ mA, $V_D = 0.7$ V and

$$R_D = \frac{V_D}{I_D} = \frac{0.7 \text{ V}}{2 \text{ mA}} = \mathbf{350\ \Omega}$$

which far exceeds the r_d of 27.5 Ω.

For $I_D = 25$ mA, $V_D = 0.79$ V and

$$R_D = \frac{V_D}{I_D} = \frac{0.79\text{ V}}{25\text{ mA}} = \mathbf{31.62\ \Omega}$$

which far exceeds the r_d of 2 Ω.

We have found the dynamic resistance graphically, but there is a basic definition in differential calculus that states:

The derivative of a function at a point is equal to the slope of the tangent line drawn at that point.

Equation (5), as defined by Fig. 26, is, therefore, essentially finding the derivative of the function at the Q-point of operation. If we find the derivative of the general equation (2) for the semiconductor diode with respect to the applied forward bias and then invert the result, we will have an equation for the dynamic or ac resistance in that region. That is, taking the derivative of Eq. (2) with respect to the applied bias will result in

$$\frac{d}{dV_D}(I_D) = \frac{d}{dV_D}\left[I_s(e^{V_D/nV_T} - 1)\right]$$

and

$$\frac{dI_D}{dV_D} = \frac{1}{nV_T}(I_D + I_s)$$

after we apply differential calculus. In general, $I_D \gg I_s$ in the vertical-slope section of the characteristics and

$$\frac{dI_D}{dV_D} \cong \frac{I_D}{nV_T}$$

Flipping the result to define a resistance ratio ($R = V/I$) gives

$$\frac{dV_D}{dI_D} = r_d = \frac{nV_T}{I_D}$$

Substituting $n = 1$ and $V_T \cong 26$ mV from Example 1 results in

$$\boxed{r_d = \frac{26\text{ mV}}{I_D}} \qquad \mathbf{(6)}$$

The significance of Eq. (6) must be clearly understood. It implies that

the dynamic resistance can be found simply by substituting the quiescent value of the diode current into the equation.

There is no need to have the characteristics available or to worry about sketching tangent lines as defined by Eq. (5). It is important to keep in mind, however, that Eq. (6) is accurate only for values of I_D in the vertical-rise section of the curve. For lesser values of I_D, $n = 2$ (silicon) and the value of r_d obtained must be multiplied by a factor of 2. For small values of I_D below the knee of the curve, Eq. (6) becomes inappropriate.

All the resistance levels determined thus far have been defined by the p–n junction and do not include the resistance of the semiconductor material itself (called *body* resistance) and the resistance introduced by the connection between the semiconductor material and the external metallic conductor (called *contact* resistance). These additional resistance levels can be included in Eq. (6) by adding a resistance denoted r_B:

$$\boxed{r'_d = \frac{26\text{ mV}}{I_D} + r_B} \quad \text{ohms} \qquad \mathbf{(7)}$$

The resistance r'_d, therefore, includes the dynamic resistance defined by Eq. (6) and the resistance r_B just introduced. The factor r_B can range from typically 0.1 Ω for high-power devices to 2 Ω for some low-power, general-purpose diodes. For Example 4 the ac resistance at 25 mA was calculated to be 2 Ω. Using Eq. (6), we have

$$r_d = \frac{26\text{ mV}}{I_D} = \frac{26\text{ mV}}{25\text{ mA}} = \mathbf{1.04\ \Omega}$$

The difference of about 1 Ω could be treated as the contribution of r_B.

For Example 4 the ac resistance at 2 mA was calculated to be 27.5 Ω. Using Eq. (6) but multiplying by a factor of 2 for this region (in the knee of the curve $n = 2$),

$$r_d = 2\left(\frac{26\text{ mV}}{I_D}\right) = 2\left(\frac{26\text{ mV}}{2\text{ mA}}\right) = 2(13\ \Omega) = \mathbf{26\ \Omega}$$

The difference of 1.5 Ω could be treated as the contribution due to r_B.

In reality, determining r_d to a high degree of accuracy from a characteristic curve using Eq. (5) is a difficult process at best and the results have to be treated with skepticism. At low levels of diode current the factor r_B is normally small enough compared to r_d to permit ignoring its impact on the ac diode resistance. At high levels of current the level of r_B may approach that of r_d, but since there will frequently be other resistive elements of a much larger magnitude in series with the diode, we will assume in this text that the ac resistance is determined solely by r_d, and the impact of r_B will be ignored unless otherwise noted. Technological improvements of recent years suggest that the level of r_B will continue to decrease in magnitude and eventually become a factor that can certainly be ignored in comparison to r_d.

The discussion above centered solely on the forward-bias region. In the reverse-bias region we will assume that the change in current along the I_s line is nil from 0 V to the Zener region and the resulting ac resistance using Eq. (5) is sufficiently high to permit the open-circuit approximation.

Typically, the ac resistance of a diode in the active region will range from about 1 Ω to 100 Ω.

Average AC Resistance

If the input signal is sufficiently large to produce a broad swing such as indicated in Fig. 28, the resistance associated with the device for this region is called the *average ac resistance*. The average ac resistance is, by definition, the resistance determined by a straight line drawn between the two intersections established by the maximum and minimum values of input voltage. In equation form (note Fig. 28),

$$\boxed{r_{\text{av}} = \frac{\Delta V_d}{\Delta I_d}\bigg|_{\text{pt. to pt.}}} \qquad \textbf{(8)}$$

For the situation indicated by Fig. 28,

$$\Delta I_d = 17\text{ mA} - 2\text{ mA} = 15\text{ mA}$$

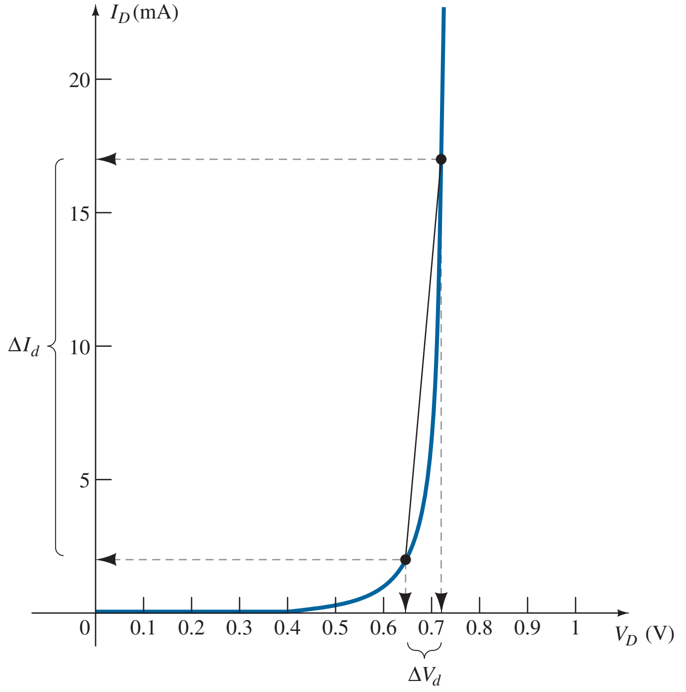


FIG. 28
Determining the average ac resistance between indicated limits.

and $$\Delta V_d = 0.725\text{ V} - 0.65\text{ V} = 0.075\text{ V}$$

with $$r_{av} = \frac{\Delta V_d}{\Delta I_d} = \frac{0.075\text{ V}}{15\text{ mA}} = \mathbf{5\ \Omega}$$

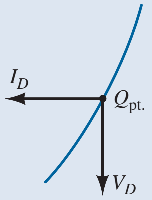
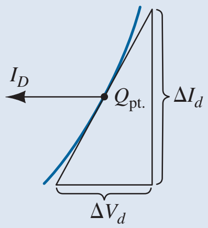
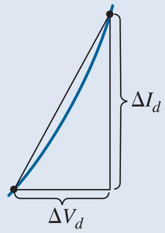
If the ac resistance (r_d) were determined at $I_D = 2$ mA, its value would be more than 5 Ω, and if determined at 17 mA, it would be less. In between, the ac resistance would make the transition from the high value at 2 mA to the lower value at 17 mA. Equation (7) defines a value that is considered the average of the ac values from 2 mA to 17 mA. The fact that one resistance level can be used for such a wide range of the characteristics will prove quite useful in the definition of equivalent circuits for a diode in a later section.

As with the dc and ac resistance levels, the lower the level of currents used to determine the average resistance, the higher is the resistance level.

Summary Table

Table 6 was developed to reinforce the important conclusions of the last few pages and to emphasize the differences among the various resistance levels. As indicated earlier, the content of this section is the foundation for a number of resistance calculations to be performed in later sections.

TABLE 6
Resistance Levels

Type	Equation	Special Characteristics	Graphical Determination
DC or static	$R_D = \dfrac{V_D}{I_D}$	Defined as a point on the characteristics	
AC or dynamic	$r_d = \dfrac{\Delta V_d}{\Delta I_d} = \dfrac{26\text{ mV}}{I_D}$	Defined by a tangent line at the Q-point	
Average ac	$r_{av} = \dfrac{\Delta V_d}{\Delta I_d}\Big\rvert_{\text{pt. to pt.}}$	Defined by a straight line between limits of operation	

9 DIODE EQUIVALENT CIRCUITS

An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device or system in a particular operating region.

In other words, once the equivalent circuit is defined, the device symbol can be removed from a schematic and the equivalent circuit inserted in its place without severely affecting the actual behavior of the system. The result is often a network that can be solved using traditional circuit analysis techniques.

Piecewise-Linear Equivalent Circuit

One technique for obtaining an equivalent circuit for a diode is to approximate the characteristics of the device by straight-line segments, as shown in Fig. 29. The resulting equivalent circuit is called a *piecewise-linear equivalent circuit.* It should be obvious from Fig. 29 that the straight-line segments do not result in an exact duplication of the actual characteristics, especially in the knee region. However, the resulting segments are sufficiently close to the actual curve to establish an equivalent circuit that will provide an excellent first approximation to the actual behavior of the device. For the sloping section of the equivalence the average ac resistance as introduced in Section 8 is the resistance level appearing in the equivalent circuit of Fig. 28 next to the actual device. In essence, it defines the resistance level of the device when it is in the "on" state. The ideal diode is included to establish that there is only one direction of conduction through the device, and a reverse-bias condition will result in the open-circuit state for the device. Since a silicon semiconductor diode does not reach the conduction state until V_D reaches 0.7 V with a forward bias (as shown in Fig. 29), a battery V_K opposing the conduction direction must appear in the equivalent circuit as shown in Fig. 30. The battery simply specifies that the voltage across the device must be greater than the threshold battery voltage before conduction through the device in the direction dictated by the ideal diode can be established. When conduction is established the resistance of the diode will be the specified value of r_{av}.

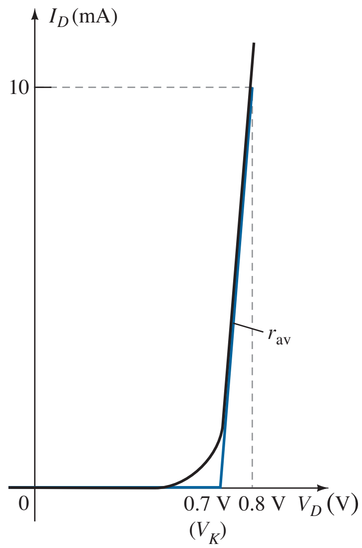


FIG. 29
Defining the piecewise-linear equivalent circuit using straight-line segments to approximate the characteristic curve.

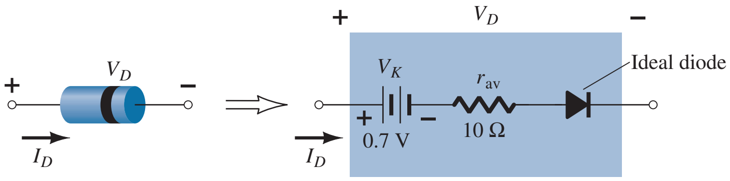


FIG. 30
Components of the piecewise-linear equivalent circuit.

Keep in mind, however, that V_K in the equivalent circuit is not an independent voltage source. If a voltmeter is placed across an isolated diode on the top of a laboratory bench, a reading of 0.7 V will not be obtained. The battery simply represents the horizontal offset of the characteristics that must be exceeded to establish conduction.

The approximate level of r_{av} can usually be determined from a specified operating point on the specification sheet (to be discussed in Section 10). For instance, for a silicon semiconductor diode, if $I_F = 10$ mA (a forward conduction current for the diode) at

$V_D = 0.8$ V, we know that for silicon a shift of 0.7 V is required before the characteristics rise, and we obtain

$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}} = \frac{0.8\text{ V} - 0.7\text{ V}}{10\text{ mA} - 0\text{ mA}} = \frac{0.1\text{ V}}{10\text{ mA}} = \mathbf{10\ \Omega}$$

as obtained for Fig. 29.

If the characteristics or specification sheet for a diode is not available the resistance r_{av} can be approximated by the ac resistance r_d.

Simplified Equivalent Circuit

For most applications, the resistance r_{av} is sufficiently small to be ignored in comparison to the other elements of the network. Removing r_{av} from the equivalent circuit is the same as implying that the characteristics of the diode appear as shown in Fig. 31. Indeed, this approximation is frequently employed in semiconductor circuit analysis. The reduced equivalent circuit appears in the same figure. It states that a forward-biased silicon diode in an electronic system under dc conditions has a drop of 0.7 V across it in the conduction state at any level of diode current (within rated values, of course).

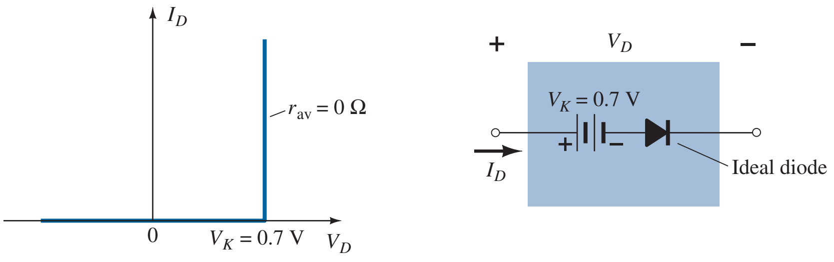


FIG. 31
Simplified equivalent circuit for the silicon semiconductor diode.

Ideal Equivalent Circuit

Now that r_{av} has been removed from the equivalent circuit, let us take the analysis a step further and establish that a 0.7-V level can often be ignored in comparison to the applied voltage level. In this case the equivalent circuit will be reduced to that of an ideal diode as shown in Fig. 32 with its characteristics.

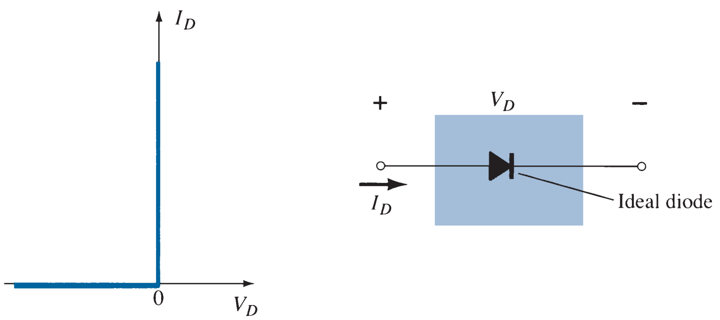


FIG. 32
Ideal diode and its characteristics.

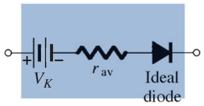
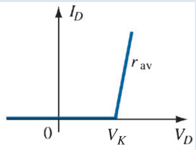
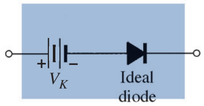
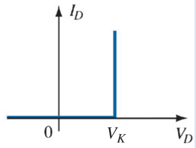
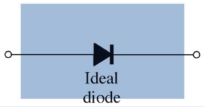
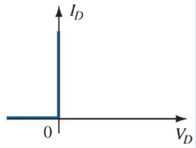
In industry a popular substitution for the phrase "diode equivalent circuit" is diode *model*—a model by definition being a representation of an existing device, object, system, and so on.

Summary Table

For clarity, the diode models employed for the range of circuit parameters and applications are provided in Table 7 with their piecewise-linear characteristics. There are always exceptions to the general rule, but it is fairly safe to say that the simplified equivalent model will

TABLE 7

Diode Equivalent Circuits (Models)

<table>
<tr><th>Type</th><th>Conditions</th><th>Model</th><th>Characteristics</th></tr>
<tr><td>Piecewise-linear model</td><td></td><td>
</td><td>
</td></tr>
<tr><td>Simplified model</td><td>$R_{\text{network}} \gg r_{\text{av}}$</td><td>
</td><td>
</td></tr>
<tr><td>Ideal device</td><td>$R_{\text{network}} \gg r_{\text{av}}$
$E_{\text{network}} \gg V_K$</td><td>
</td><td>
</td></tr>
</table>

be employed most frequently in the analysis of electronic systems, whereas the ideal diode is frequently applied in the analysis of power supply systems where larger voltages are encountered.

10 TRANSITION AND DIFFUSION CAPACITANCE

It is important to realize that:

Every electronic or electrical device is frequency sensitive.

That is, the terminal characteristics of any device will change with frequency. Even the resistance of a basic resistor, as of any construction, will be sensitive to the applied frequency. At low to mid-frequencies most resistors can be considered fixed in value. However, as we approach high frequencies, stray capacitive and inductive effects start to play a role and will affect the total impedance level of the element.

For the diode it is the stray capacitance levels that have the greatest effect. At low frequencies and relatively small levels of capacitance the reactance of a capacitor, determined by $X_C = 1/2\pi fC$, is usually so high it can be considered infinite in magnitude, represented by an open circuit, and ignored. At high frequencies, however, the level of X_C can drop to the point where it will introduce a low-reactance "shorting" path. If this shorting path is across the diode, it can essentially keep the diode from affecting the response of the network.

In the p–n semiconductor diode, there are two capacitive effects to be considered. Both types of capacitance are present in the forward- and reverse-bias regions, but one so outweighs the other in each region that we consider the effects of only one in each region.

Recall that the basic equation for the capacitance of a parallel-plate capacitor is defined by $C = \epsilon A/d$, where ϵ is the permittivity of the dielectric (insulator) between the plates of area A separated by a distance d. In a diode the depletion region (free of carriers) behaves essentially like an insulator between the layers of opposite charge. Since the depletion width (d) will increase with increased reverse-bias potential, the resulting transition capacitance will decrease, as shown in Fig. 33. The fact that the capacitance is dependent on the applied reverse-bias potential has application in a number of electronic systems.

This capacitance, called the transition (C_T), barriers, or depletion region capacitance, is determined by

$$\boxed{C_T = \frac{C(0)}{(1 + |V_R/V_K|)^n}} \qquad \textbf{(9)}$$

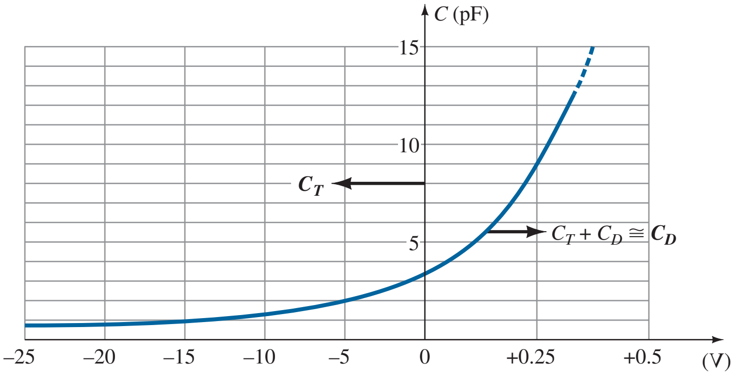


FIG. 33
Transition and diffusion capacitance versus applied bias for a silicon diode.

where $C(0)$ is the capacitance under no-bias conditions and V_R is the applied reverse bias potential. The power n is ½ or ⅓ depending on the manufacturing process for the diode.

Although the effect described above will also be present in the forward-bias region, it is overshadowed by a capacitance effect directly dependent on the rate at which charge is injected into the regions just outside the depletion region. The result is that increased levels of current will result in increased levels of diffusion capacitance (C_D) as demonstrated by the following equation:

$$\boxed{C_D = \left(\frac{\tau_\tau}{V_K}\right) I_D} \qquad \textbf{(10)}$$

where τ_τ is the minority carrier lifetime—the time is world take for a minority carrier such as a hole to recombine with an electron in the n-type material. However, increased levels of current result in a reduced level of associated resistance (to be demonstrated shortly), and the resulting time constant ($\tau = RC$), which is very important in high-speed applications, does not become excessive.

In general, therefore,

the transition capacitance is the predominant capacitive effect in the reverse-bias region whereas the diffusion capacitance is the predominant capacitive effect in the forward-bias region.

The capacitive effects described above are represented by capacitors in parallel with the ideal diode, as shown in Fig. 34. For low- or mid-frequency applications (except in the power area), however, the capacitor is normally not included in the diode symbol.

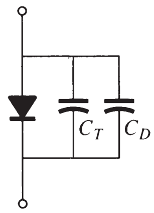


FIG. 34
Including the effect of the transition or diffusion capacitance on the semiconductor diode.

11 REVERSE RECOVERY TIME

There are certain pieces of data that are normally provided on diode specification sheets provided by manufacturers. One such quantity that has not been considered yet is the reverse recovery time, denoted by t_{rr}. In the forward-bias state it was shown earlier that there are a large number of electrons from the n-type material progressing through the p-type material and a large number of holes in the n-type material—a requirement for conduction. The electrons in the p-type material and holes progressing through the n-type material establish a large number of minority carriers in each material. If the applied voltage should be reversed to establish a reverse-bias situation, we would ideally like to see the diode change instantaneously from the conduction state to the nonconduction state. However, because of the large number of minority carriers in each material, the diode current will simply reverse as shown in Fig. 35 and stay at this measurable level for the period of time t_s (storage time) required for the minority carriers to return to their majority-carrier state in the opposite material. In essence, the diode will remain in the short-circuit state with a current I_{reverse} determined by the network parameters. Eventually, when this storage phase has passed, the current will be reduced in level to that associated with the nonconduction state. This second period of time is denoted by t_t (transition interval). The reverse recovery time is the sum of these two intervals: $t_{rr} = t_s + t_t$. This is an important consideration in

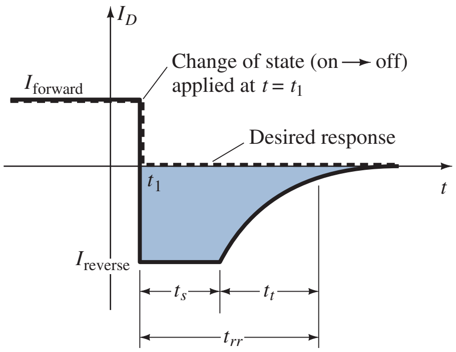


FIG. 35
Defining the reverse recovery time.

high-speed switching applications. Most commercially available switching diodes have a t_{rr} in the range of a few nanoseconds to 1 μs. Units are available, however, with a t_{rr} of only a few hundred picoseconds (10^{-12} s).

12 DIODE SPECIFICATION SHEETS

Data on specific semiconductor devices are normally provided by the manufacturer in one of two forms. Most frequently, they give a very brief description limited to perhaps one page. At other times, they give a thorough examination of the characteristics using graphs, artwork, tables, and so on. In either case, there are specific pieces of data that must be included for proper use of the device. They include:

1. The forward voltage V_F (at a specified current and temperature)
2. The maximum forward current I_F (at a specified temperature)
3. The reverse saturation current I_R (at a specified voltage and temperature)
4. The reverse-voltage rating [PIV or PRV or V(BR), where BR comes from the term "breakdown" (at a specified temperature)]
5. The maximum power dissipation level at a particular temperature
6. Capacitance levels
7. Reverse recovery time t_{rr}
8. Operating temperature range

Depending on the type of diode being considered, additional data may also be provided, such as frequency range, noise level, switching time, thermal resistance levels, and peak repetitive values. For the application in mind, the significance of the data will usually be self-apparent. If the maximum power or dissipation rating is also provided, it is understood to be equal to the following product:

$$\boxed{P_{D\max} = V_D I_D} \tag{11}$$

where I_D and V_D are the diode current and voltage, respectively, at a particular point of operation.

If we apply the simplified model for a particular application (a common occurrence), we can substitute $V_D = V_T = 0.7$ V for a silicon diode in Eq. (11) and determine the resulting power dissipation for comparison against the maximum power rating. That is,

$$\boxed{P_{\text{dissipated}} \cong (0.7\text{ V})I_D} \tag{12}$$

The data provided for a high-voltage/low-leakage diode appear in Figs. 36 and 37. This example would represent the expanded list of data and characteristics. The term *rectifier* is applied to a diode when it is frequently used in a *rectification* process.

Specific areas of the specification sheet are highlighted in blue, with letters corresponding to the following description:

A The data sheet highlights the fact that the silicon high-voltage diode has a *minimum* reverse-bias voltage of 125 V at a specified reverse-bias current.

B Note the wide range of temperature operation. Always be aware that data sheets typically use the centigrade scale, with 200°C = 392°F and −65°C = −85°F.

C The maximum power dissipation level is given by $P_D = V_D I_D = 500\text{ mW} = 0.5\text{ W}$. The effect of the linear derating factor of 3.33 mW/°C is demonstrated in Fig. 37a. Once the temperature exceeds 25°C the maximum power rating will drop by 3.33 mW for each 1°C increase in temperature. At a temperature of 100°C, which is the boiling point of water, the maximum power rating has dropped to one half of its original value. An initial temperature of 25°C is typical inside a cabinet containing operating electronic equipment in a low-power situation.

D The maximum sustainable current is 500 mA. The plot of Fig. 37b reveals that the forward current at 0.5 V is about 0.01 mA, but jumps to 1 mA (100 times greater) at about 0.65 V. At 0.8 V the current is more than 10 mA, and just above 0.9 V it is close

DIFFUSED SILICON PLANAR

A — • BV . . . 125 V (MIN) @ 100 µA (BAY73)

ABSOLUTE MAXIMUM RATINGS (Note 1)

Temperatures

B	Storage Temperature Range	–65°C to +200°C
	Maximum Junction Operating Temperature	+175°C
	Lead Temperature	+260°C

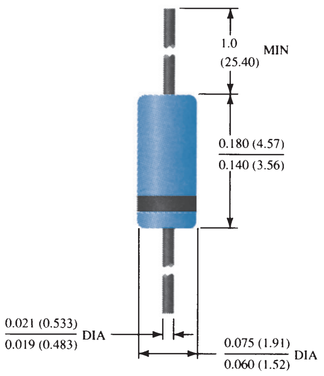
Power Dissipation (Note 2)

C	Maximum Total Power Dissipation at 25°C Ambient	500 mW
	Linear Power Derating Factor (from 25°C)	3.33 mW/°C

Maximum Voltage and Currents

	WIV	Working Inverse Voltage	BAY73	100 V
	I_O	Average Rectified Current		200 mA
D	I_F	Continuous Forward Current		500 mA
	i_f	Peak Repetitive Forward Current		600 mA
	$i_{f\,(surge)}$	Peak Forward Surge Current		
		Pulse Width = 1 s		1.0 A
		Pulse Width = 1 µs		4.0 A

DO-35 OUTLINE



NOTES:
Copper clad steel leads, tin plated
Gold plated leads available
Hermetically sealed glass package
Package weight is 0.14 gram

ELECTRICAL CHARACTERISTICS (25°C Ambient Temperature unless otherwise noted)

	SYMBOL	CHARACTERISTIC	BAY73 MIN	BAY73 MAX	UNITS	TEST CONDITIONS
E	V_F	Forward Voltage	0.85	1.00	V	I_F = 200 mA
			0.81	0.94	V	I_F = 100 mA
			0.78	0.88	V	I_F = 50 mA
			0.69	0.80	V	I_F = 10 mA
			0.67	0.75	V	I_F = 5.0 mA
			0.60	0.68	V	I_F = 1.0 mA
F	I_R	Reverse Current		500	nA	V_R = 20 V, T_A = 125°C
				1.0	µA	V_R = 100 V, T_A = 125°C
				0.2	nA	V_R = 20 V, T_A = 25°C
				0.5	nA	V_R = 100 V, T_A = 25°C
	BV	Breakdown Voltage	125		V	I_R = 100 µA
G	C	Capacitance		5.0	pF	V_R = 0, f = 1.0 MHz
H	t_{rr}	Reverse Recovery Time		3.0	µs	I_F = 10 mA, V_R = 35 V R_L = 1.0 to 100 kΩ C_L = 10 pF, JAN 256

NOTES
1 These ratings are limiting values above which the serviceability of the diode may be impaired.
2 These are steady state limits. The factory should be consulted on applications involving pulses or low duty-cycle operation.

FIG. 36

Electrical characteristics of a high-voltage, low-leakage diode.

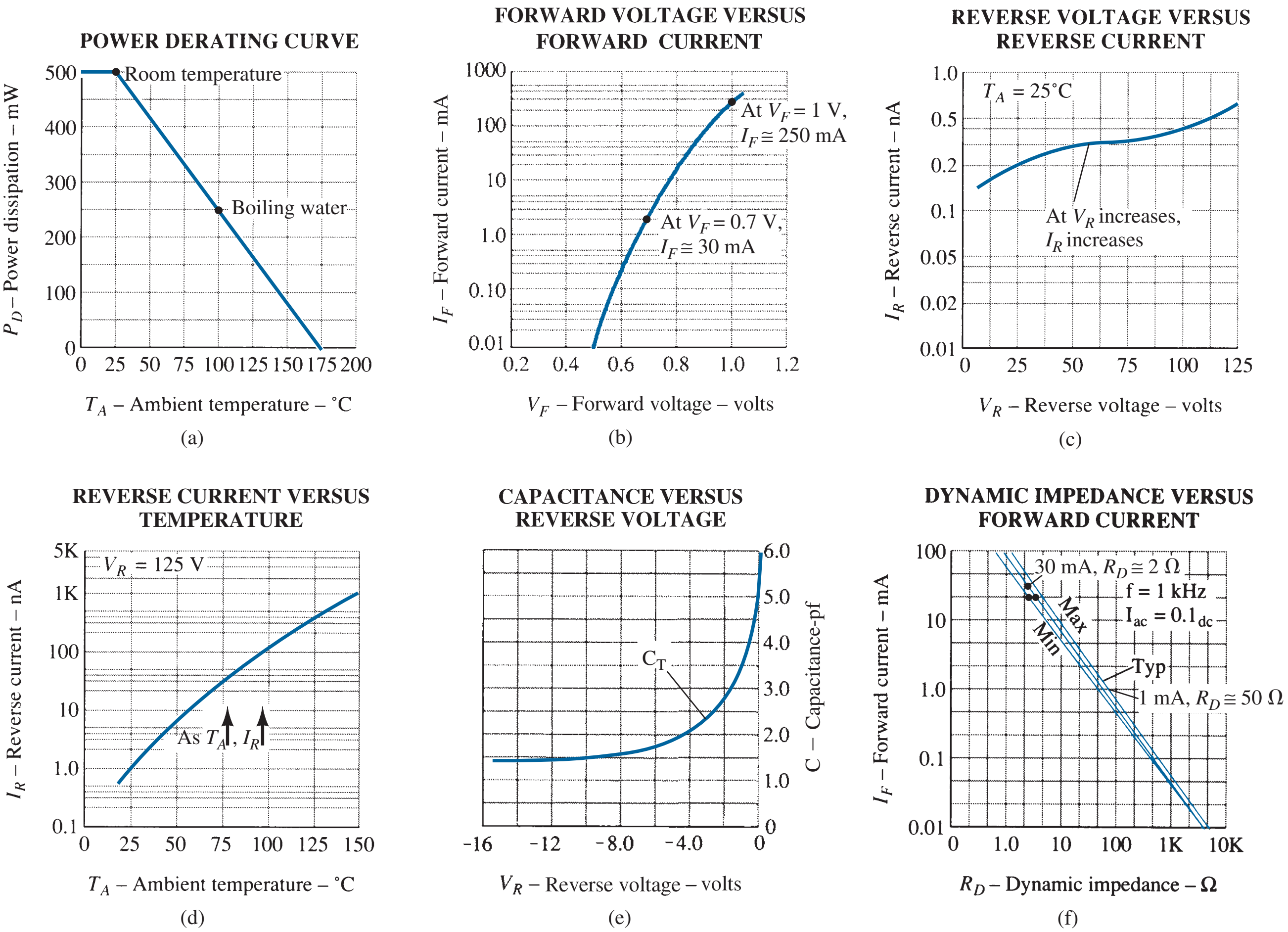


FIG. 37

Terminal characteristics of a high-voltage diode.

to 100 mA. The curve of Fig. 37b certainly looks nothing like the characteristic curves appearing in the last few sections. This is a result of using a log scale for the current and a linear scale for the voltage.

Log scales are often used to provide a broader range of values for a variable in a limited amount of space.

If a linear scale was used for the current, it would be impossible to show a range of values from 0.01 mA to 1000 mA. If the vertical divisions were in 0.01-mA increments, it would take 100,000 equal intervals on the vertical axis to reach 1000 mA. For the moment recognize that the voltage level at given levels of current can be found by using the intersection with the curve. For vertical values above a level such as 1.0 mA, the next level is 2 mA, followed by 3 mA, 4 mA, and 5 mA. The levels of 6 mA to 10 mA can be determined by simply dividing the distance into equal intervals (not the true distribution, but close enough for the provided graphs). For the next level it would be 10 mA, 20 mA, 30 mA, and so on. The graph of Fig. 37b is called a *semi-log plot* to reflect the fact that only one axis uses a log scale.

E The data provide a range of V_F (forward-bias voltages) for each current level. The higher the forward current, the higher is the applied forward bias. At 1 mA we find V_F can range from 0.6 V to 0.68 V, but at 200 mA it can be as high as 0.85 V to 1.00 V. For the full range of current levels with 0.6 V at 1 mA and 0.85 V at 200 mA it is certainly a reasonable approximation to use 0.7 V as the average value.

F The data provided clearly reveal how the reverse saturation current increases with applied reverse bias at a fixed temperature. At 25°C the maximum reverse-bias current increases from 0.2 nA to 0.5 nA due to an increase in reverse-bias voltage by the same factor of 5. At 125°C it jumps by a factor of 2 to the high level of 1 μA. Note the extreme change in reverse saturation current with temperature as the maximum current rating jumps from 0.2 nA at 25°C to 500 nA at 125°C (at a fixed reverse-bias voltage of 20 V). A similar increase occurs at a reverse-bias potential of 100 V. The semi-log plots of Figs. 37c and 37d provide an indication of how the reverse saturation current changes with changes in reverse voltage and temperature. At first glance Fig. 37c might suggest that the reverse saturation current is fairly steady for changes in reverse voltage. However, this can sometimes be the effect of using a log scale for the vertical axis. The current has actually changed from a level of 0.2 nA to a level of 0.7 nA for the range of voltages representing a change of almost 6 to 1. The dramatic effect of temperature on the reverse saturation current is clearly displayed in Fig. 37d. At a reverse-bias voltage of 125 V the reverse-bias current increases from a level of about 1 nA at 25°C to about 1 μA at 150°C, an increase of a factor of 1000 over the initial value.

Temperature and applied reverse bias are very important factors in designs sensitive to the reverse saturation current.

G As shown in the data listing and on Fig. 37e, the transition capacitance at a reverse-bias voltage of 0 V is 5 pF at a test frequency of 1 MHz. Note the severe change in capacitance level as the reverse-bias voltage is increased. As mentioned earlier, this sensitive region can be put to good use in the design of a device (Varactor) whose terminal capacitance is sensitive to the applied voltage.

H The reverse recovery time is 3 μs for the test conditions shown. This is not a fast time for some of the current high-performance systems in use today. However, for a variety of low- and mid-frequency applications it is acceptable.

The curves of Fig. 37f provide an indication of the magnitude of the ac resistance of the diode versus forward current. Section 8 clearly demonstrated that the dynamic resistance of a diode decreases with increase in current. As we go up the current axis of Fig. 37f it is clear that if we follow the curve, the dynamic resistance will decrease. At 0.1 mA it is close to 1 kΩ; at 10 mA, 10 Ω; and at 100 mA, only 1 Ω; this clearly supports the earlier discussion. Unless one has had experience reading log scales, the curve is challenging to read for levels between those indicated because it is a *log–log* plot. Both the vertical axis and the horizontal axis employ a log scale.

The more one is exposed to specification sheets, the "friendlier" they will become, especially when the impact of each parameter is clearly understood for the application under investigation.

13 SEMICONDUCTOR DIODE NOTATION

The notation most frequently used for semiconductor diodes is provided in Fig. 38. For most diodes any marking such as a dot or band, as shown in Fig. 38, appears at the cathode end. The terminology anode and cathode is a carryover from vacuum-tube notation. The anode refers to the higher or positive potential, and the cathode refers to the lower or negative terminal. This combination of bias levels will result in a forward-bias or "on" condition for the diode. A number of commercially available semiconductor diodes appear in Fig. 39.

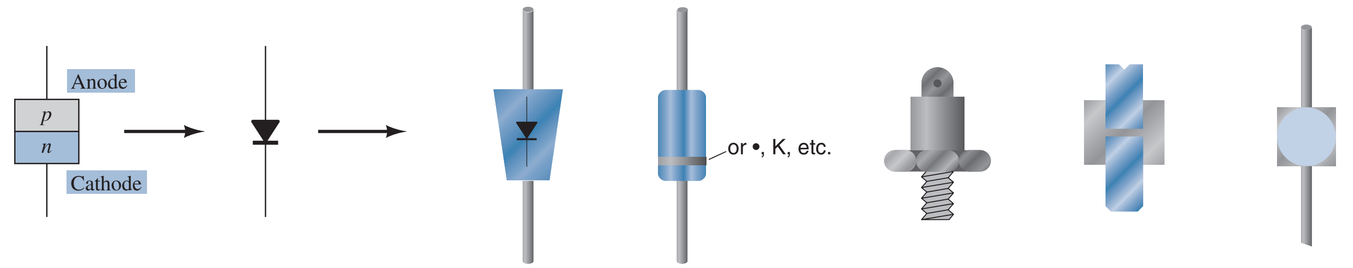


FIG. 38
Semiconductor diode notation.

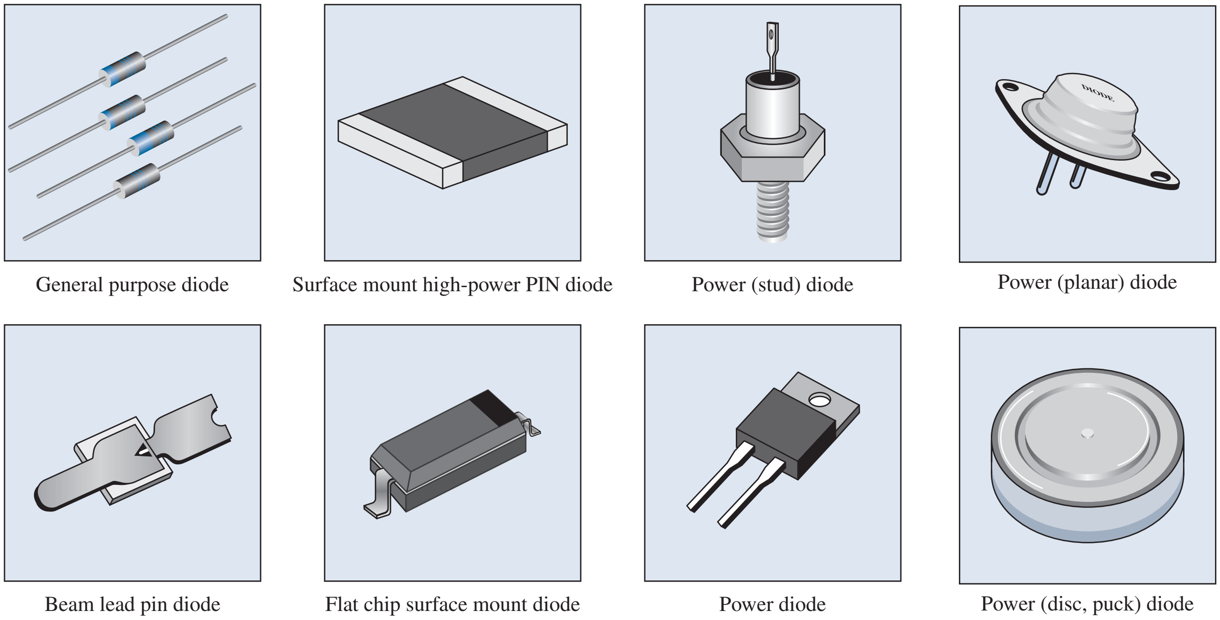


FIG. 39
Various types of junction diodes.

14 DIODE TESTING

The condition of a semiconductor diode can be determined quickly using (1) a digital display meter (DDM) with a *diode checking function*, (2) the *ohmmeter section* of a multimeter, or (3) a *curve tracer.*

Diode Checking Function

A digital display meter with a diode checking capability appears in Fig. 40. Note the small diode symbol at the top right of the rotating dial. When set in this position and hooked up as shown in Fig. 41a, the diode should be in the "on" state and the display will provide an indication of the forward-bias voltage such as 0.67 V (for Si). The meter has an internal constant-current source (about 2 mA) that will define the voltage level as indicated in Fig. 41b. An OL indication with the hookup of Fig. 41a reveals an open (defective) diode. If the leads are reversed, an OL indication should result due to the expected open-circuit equivalence for the diode. In general, therefore, an OL indication in both directions is an indication of an open or defective diode.

FIG. 40
Digital display meter. (Courtesy of B&K Precision Corporation.)

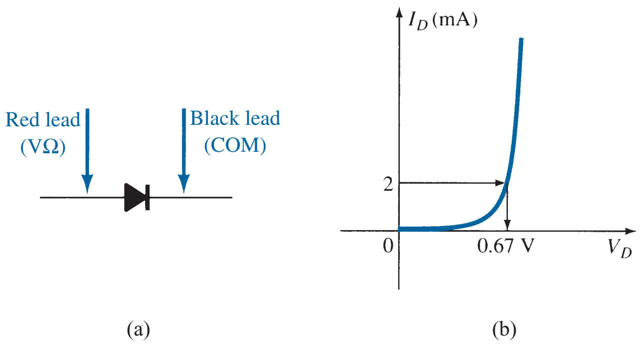


FIG. 41
Checking a diode in the forward-bias state.

Ohmmeter Testing

In Section 8 we found that the forward-bias resistance of a semiconductor diode is quite low compared to the reverse-bias level. Therefore, if we measure the resistance of a diode using the connections indicated in Fig. 42, we can expect a relatively low level. The resulting ohmmeter indication will be a function of the current established through the diode by the internal battery (often 1.5 V) of the ohmmeter circuit. The higher the current, the lower is the resistance level. For the reverse-bias situation the reading should be quite high, requiring a high resistance scale on the meter, as indicated in Fig. 42b. A high resistance reading in both directions indicates an open (defective-device) condition, whereas a very low resistance reading in both directions will probably indicate a shorted device.

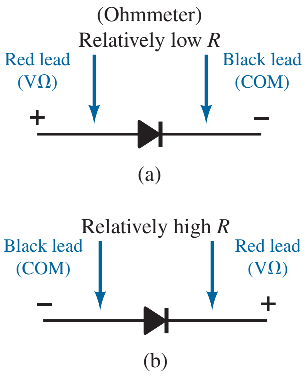


FIG. 42
Checking a diode with an ohmmeter.

Curve Tracer

The curve tracer of Fig. 43 can display the characteristics of a host of devices, including the semiconductor diode. By properly connecting the diode to the test panel at the bottom center of the unit and adjusting the controls, one can obtain the display of Fig. 44. Note that the vertical scaling is 1 mA/div, resulting in the levels indicated. For the horizontal axis the scaling is 100 mV/div, resulting in the voltage levels indicated. For a 2-mA level as defined for a DDM, the resulting voltage would be about 625 mV = 0.625 V. Although the instrument initially appears quite complex, the instruction manual and a few moments of exposure will reveal that the desired results can usually be obtained without an excessive amount of effort and time.

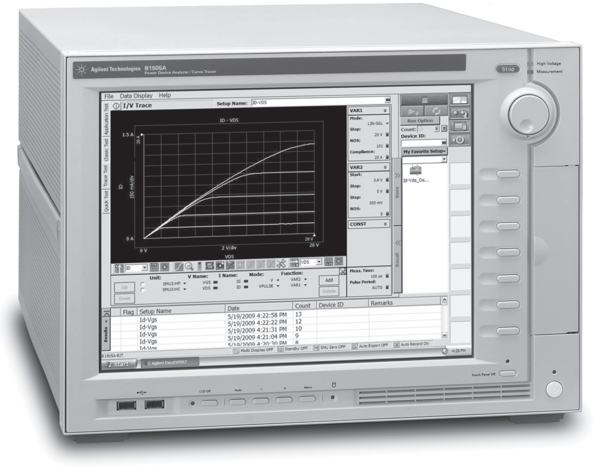


FIG. 43
Curve tracer. (© Agilent Technologies, Inc. Reproduced with Permission, Courtesy of Agilent Technologies, Inc.)

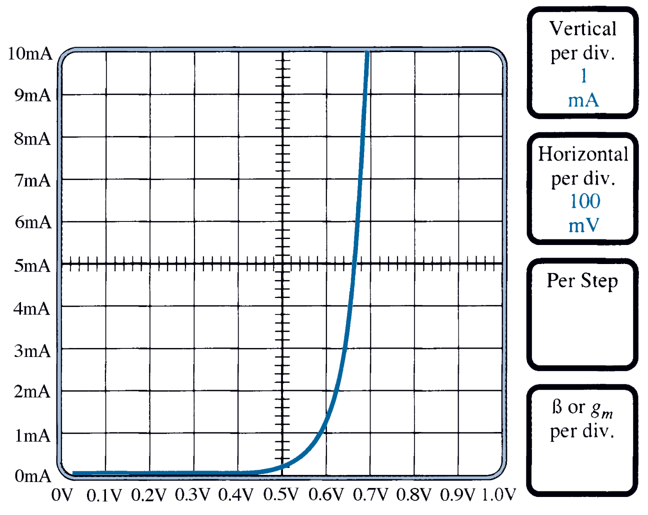


FIG. 44
Curve tracer response to IN4007 silicon diode.

15 ZENER DIODES

The Zener region of Fig. 45 was discussed in some detail in Section 6. The characteristic drops in an almost vertical manner at a reverse-bias potential denoted V_Z. The fact that the curve drops down and away from the horizontal axis rather than up and away for the positive-V_D region reveals that the current in the Zener region has a direction opposite to that of a forward-biased diode. The slight slope to the curve in the Zener region reveals that there is a level of resistance to be associated with the Zener diode in the conduction mode.

This region of unique characteristics is employed in the design of *Zener diodes*, which have the graphic symbol appearing in Fig. 46a. The semiconductor diode and the Zener diode are presented side by side in Fig. 46 to ensure that the direction of conduction of each is clearly understood together with the required polarity of the applied voltage. For the semiconductor diode the "on" state will support a current in the direction of the arrow in the symbol. For the Zener diode the direction of conduction is opposite to that of the arrow in the symbol, as pointed out in the introduction to this section. Note also that the polarity of V_D and V_Z are the same as would be obtained if each were a resistive element as shown in Fig. 46c.

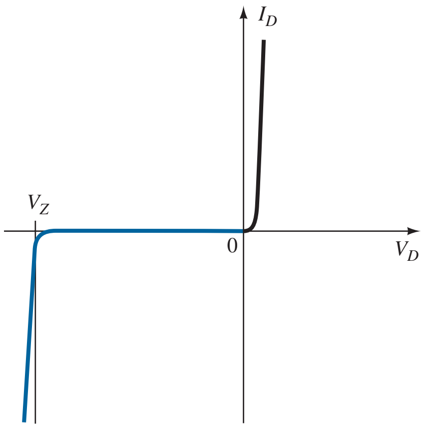


FIG. 45
Reviewing the Zener region.

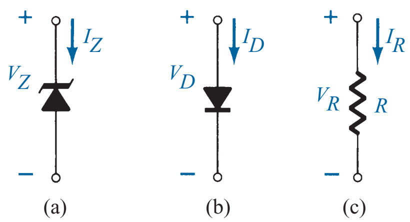


FIG. 46
Conduction direction: (a) Zener diode; (b) semiconductor diode; (c) resistive element.

The location of the Zener region can be controlled by varying the doping levels. An increase in doping that produces an increase in the number of added impurities, will decrease the Zener potential. Zener diodes are available having Zener potentials of 1.8 V to 200 V with power ratings from ¼ W to 50 W. Because of its excellent temperature and current capabilities, silicon is the preferred material in the manufacture of Zener diodes.

It would be nice to assume the Zener diode is ideal with a straight vertical line at the Zener potential. However, there is a slight slope to the characteristics requiring the piecewise equivalent model appearing in Fig. 47 for that region. For most of the applications appearing in this text the series resistive element can be ignored and the reduced equivalent model of just a dc battery of V_Z volts employed. Since some applications of Zener diodes swing between the Zener region and the forward-bias region, it is important to understand the operation of the Zener diode in all regions. As shown in Fig. 47, the equivalent model for a Zener diode in the reverse-bias region below V_Z is a very large resistor (as for the standard diode). For most applications this resistance is so large it can be ignored and the open-circuit equivalent employed. For the forward-bias region the piecewise equivalent is the same as described in earlier sections.

The specification sheet for a 10-V, 500-mW, 20% Zener diode is provided as Table 8, and a plot of the important parameters is given in Fig. 48. The term *nominal* used in the specification of the Zener voltage simply indicates that it is a typical average value. Since this is a 20% diode, the Zener potential of the unit one picks out of a *lot* (a term used to describe a package of diodes) can be expected to vary as 10 V + 20%, or from 8 V to 12 V. Both 10% and 50% diodes are also readily available. The test current I_{ZT} is the current defined by the

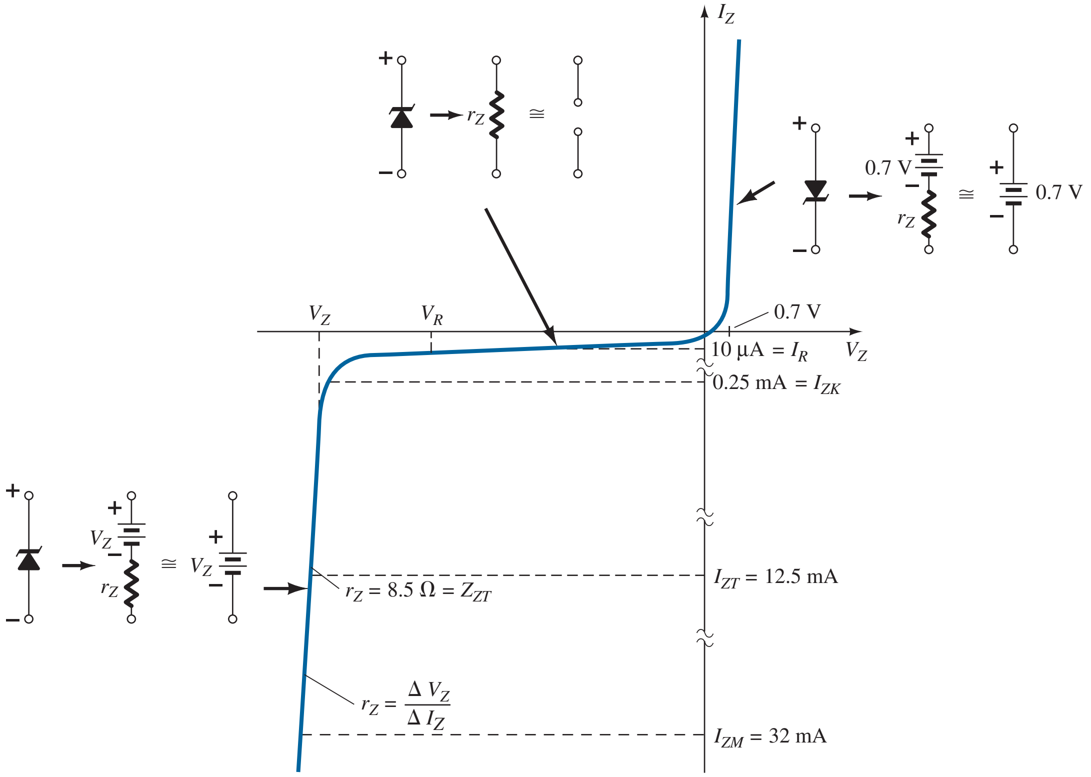


FIG. 47

Zener diode characteristics with the equivalent model for each region.

TABLE 8

Electrical Characteristics (25°C Ambient Temperature)

Zener Voltage Nominal V_Z (V)	Test Current I_{ZT} (mA)	Maximum Dynamic Impedance Z_{ZT} at I_{ZT} (Ω)	Maximum Knee Impedance Z_{ZK} at I_{ZK} (Ω)	(mA)	Maximum Reverse Current I_R at V_R (µA)	Test Voltage V_R (V)	Maximum Regulator Current I_{ZM} (mA)	Typical Temperature Coefficient (%/°C)
10	12.5	8.5	700	0.25	10	7.2	32	+0.072

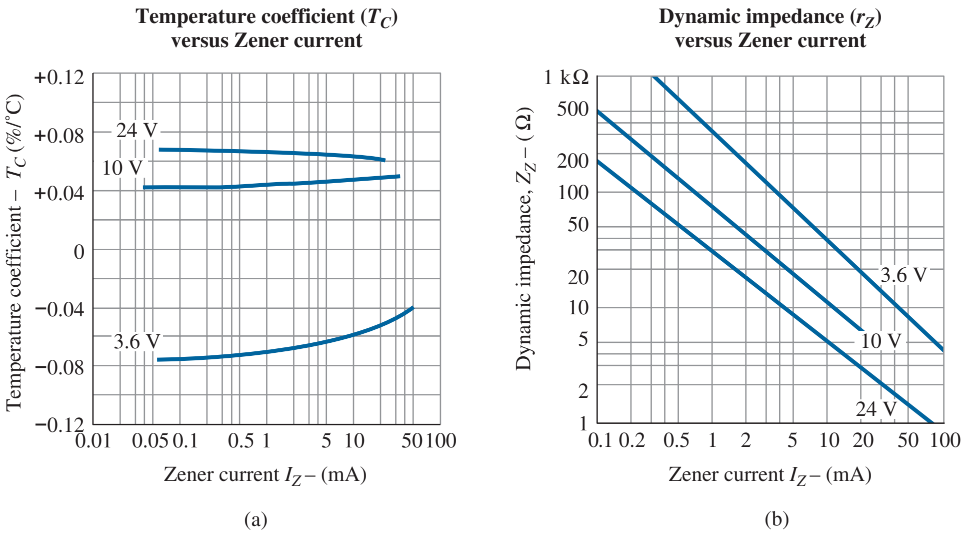


FIG. 48

Electrical characteristics for a 10-V, 500-mW Zener diode.

¼-power level. It is the current that will define the dynamic resistance Z_{ZT} and appears in the general equation for the power rating of the device. That is,

$$\boxed{P_{Z_{max}} = 4I_{ZT}V_Z} \tag{13}$$

Substituting I_{ZT} into the equation with the nominal Zener voltage results in

$$P_{Z_{max}} = 4I_{ZT}V_Z = 4(12.5 \text{ mA})(10 \text{ V}) = 500 \text{ mW}$$

which matches the 500-mW label appearing above. For this device the dynamic resistance is 8.5 Ω, which is usually small enough to be ignored in most applications. The maximum knee impedance is defined at the center of the knee at a current of $I_{ZK} = 0.25$ mA. Note that in all the above the letter T is used in subscripts to indicate test values and the letter K to indicate knee values. For any level of current below 0.25 mA the resistance will only get larger in the reverse-bias region. The knee value therefore reveals when the diode will start to show very high series resistance elements that one may not be able to ignore in an application. Certainly 500 Ω = 0.5 kΩ may be a level that can come into play. At a reverse-bias voltage the application of a test voltage of 7.2 V results in a reverse saturation current of 10 μA, a level that could be of some concern in some applications. The maximum regulator current is the maximum continuous current one would want to support in the use of the Zener diode in a regulator configuration. Finally, we have the temperature coefficient (T_C) in percent per degree centigrade.

The Zener potential of a Zener diode is very sensitive to the temperature of operation.

The temperature coefficient can be used to find the change in Zener potential due to a change in temperature using the following equation:

$$\boxed{T_C = \frac{\Delta V_Z/V_Z}{T_1 - T_0} \times 100\%/°\text{C}} \quad (\%/°\text{C}) \tag{14}$$

where T_1 is the new temperature level
T_0 is room temperature in an enclosed cabinet (25°C)
T_C is the temperature coefficient
and V_Z is the nominal Zener potential at 25°C.

To demonstrate the effect of the temperature coefficient on the Zener potential, consider the following example.

EXAMPLE 5 Analyze the 10-V Zener diode described by Table 7 if the temperature is increased to 100°C (the boiling point of water).

Solution: Substituting into Eq. (14), we obtain

$$\Delta V_Z = \frac{T_C V_Z}{100\%}(T_1 - T_0)$$

$$= \frac{(0.072\%/°\text{C})(10 \text{ V})}{100\%}(100°\text{C} - 25°\text{C})$$

and $\Delta V_Z = 0.54 \text{ V}$

The resulting Zener potential is now

$$V_Z' = V_Z + 0.54 \text{ V} = \mathbf{10.54 \text{ V}}$$

which is not an insignificant change.

It is important to realize that in this case the temperature coefficient was positive. For Zener diodes with Zener potentials less than 5 V it is very common to see negative temperature coefficients, where the Zener voltage drops with an increase in temperature. Figure 48a provides a plot of T versus Zener current for three different levels of diodes. Note that the 3.6-V diode has a negative temperature coefficient, whereas the others have positive values.

The change in dynamic resistance with current for the Zener diode in its avalanche region is provided in Fig. 48b. Again, we have a log–log plot, which has to be carefully read.

Initially it would appear that there is an inverse linear relationship between the dynamic resistance because of the straight line. That would imply that if one doubles the current, one cuts the resistance in half. However, it is only the log–log plot that gives this impression, because if we plot the dynamic resistance for the 24-V Zener diode versus current using linear scales we obtain the plot of Fig. 49, which is almost exponential in appearance. Note on both plots that the dynamic resistance at very low currents that enter the knee of the curve is fairly high at about 200 Ω. However, at higher Zener currents, away from the knee, at, say 10 mA, the dynamic resistance drops to about 5 Ω.

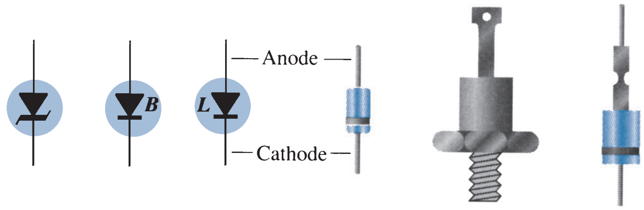


FIG. 49
Zener terminal identification and symbols.

The terminal identification and the casing for a variety of Zener diodes appear in Fig. 49. Their appearance is similar in many ways to that of the standard diode.

16 LIGHT-EMITTING DIODES

The increasing use of digital displays in calculators, watches, and all forms of instrumentation has contributed to an extensive interest in structures that emit light when properly biased. The two types in common use to perform this function are the light-emitting diode (LED) and the liquid-crystal display (LCD). Since the LED falls within the family of *p–n* junction devices, it will be introduced in this chapter.

As the name implies, the light-emitting diode is a diode that gives off visible or invisible (infrared) light when energized. In any forward-biased *p–n* junction there is, within the structure and primarily close to the junction, a recombination of holes and electrons. This recombination requires that the energy possessed by the unbound free electrons be transferred to another state. In all semiconductor *p–n* junctions some of this energy is given off in the form of heat and some in the form of photons.

In Si and Ge diodes the greater percentage of the energy converted during recombination at the junction is dissipated in the form of heat within the structure, and the emitted light is insignificant.

For this reason, silicon and germanium are not used in the construction of LED devices. On the other hand:

Diodes constructed of GaAs emit light in the infrared (invisible) zone during the recombination process at the p–n junction.

Even though the light is not visible, infrared LEDs have numerous applications where visible light is not a desirable effect. These include security systems, industrial processing, optical coupling, safety controls such as on garage door openers, and in home entertainment centers, where the infrared light of the remote control is the controlling element.

Through other combinations of elements a coherent visible light can be generated. Table 9 provides a list of common compound semiconductors and the light they generate. In addition, the typical range of forward bias potentials for each is listed.

The basic construction of an LED appears in Fig. 50 with the standard symbol used for the device. The external metallic conducting surface connected to the *p*-type material is smaller to permit the emergence of the maximum number of photons of light energy when the device is forward-biased. Note in the figure that the recombination of the injected carriers due to the forward-biased junction results in emitted light at the site of the recombination.

TABLE 9
Light-Emitting Diodes

Color	Construction	Typical Forward Voltage (V)
Amber	AlInGaP	2.1
Blue	GaN	5.0
Green	GaP	2.2
Orange	GaAsP	2.0
Red	GaAsP	1.8
White	GaN	4.1
Yellow	AlInGaP	2.1

There will, of course, be some absorption of the packages of photon energy in the structure itself, but a very large percentage can leave, as shown in the figure.

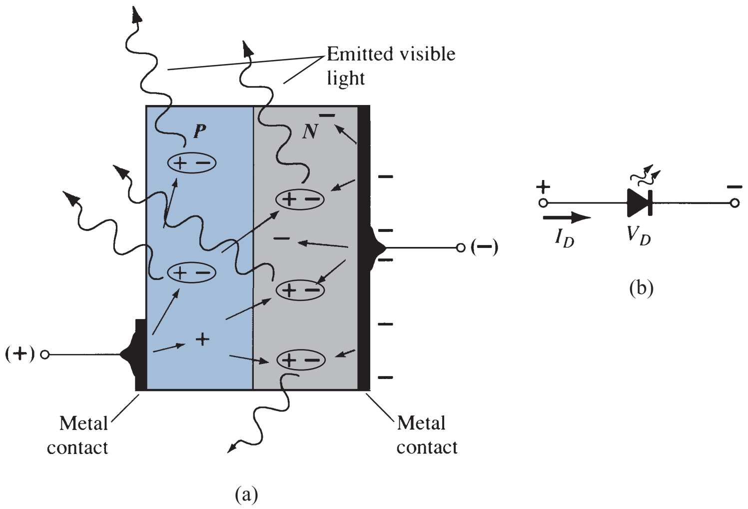


FIG. 50
(a) Process of electroluminescence in the LED; (b) graphic symbol.

Just as different sounds have different frequency spectra (high-pitched sounds generally have high-frequency components, and low sounds have a variety of low-frequency components), the same is true for different light emissions.

The frequency spectrum for infrared light extends from about 100 THz (T = tera = 10^{12}) to 400 THz, with the visible light spectrum extending from about 400 to 750 THz.

It is interesting to note that invisible light has a lower frequency spectrum than visible light.

In general, when one talks about the response of electroluminescent devices, one references their wavelength rather than their frequency.

The two quantities are related by the following equation:

$$\boxed{\lambda = \frac{c}{f}} \quad \text{(m)} \tag{15}$$

where $c = 3 \times 10^8$ m/s (the speed of light in a vacuum)
f = frequency in Hertz
λ = wavelength in meters.

EXAMPLE 6 Using Eq. (15), find the range of wavelength for the frequency range of visible light (400 THz–750 THz).

Solution:

$$c = 3 \times 10^8 \frac{\cancel{m}}{s}\left[\frac{10^9\ \text{nm}}{\cancel{m}}\right] = 3 \times 10^{17}\ \text{nm/s}$$

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{17}\ \text{nm/s}}{400\ \text{THz}} = \frac{3 \times 10^{17}\ \text{nm/s}}{400 \times 10^{12}\ \text{Hz}} = 750\ \text{nm}$$

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{17}\ \text{nm/s}}{750\ \text{THz}} = \frac{3 \times 10^{17}\ \text{nm/s}}{750 \times 10^{12}\ \text{Hz}} = 400\ \text{nm}$$

400 nm to 750 nm

Note in the above example the resulting inversion from higher frequency to smaller wavelength. That is, the higher frequency results in the smaller wavelength. Also, most charts use either nanometers (nm) or angstrom (Å) units. One angstrom unit is equal to 10^{-10} m.

The response of the average human eye as provided in Fig. 51 extends from about 350 nm to 800 nm with a peak near 550 nm.

It is interesting to note that the peak response of the eye is to the color green, with red and blue at the lower ends of the bell curve. The curve reveals that a red or a blue LED must have a much stronger efficiency than a green one to be visible at the same intensity. In other words, the eye is more sensitive to the color green than to other colors. Keep in mind that the wavelengths shown are for the peak response of each color. All the colors indicated on the plot will have a bell-shaped curve response, so green, for example, is still visible at 600 nm, but at a lower intensity level.

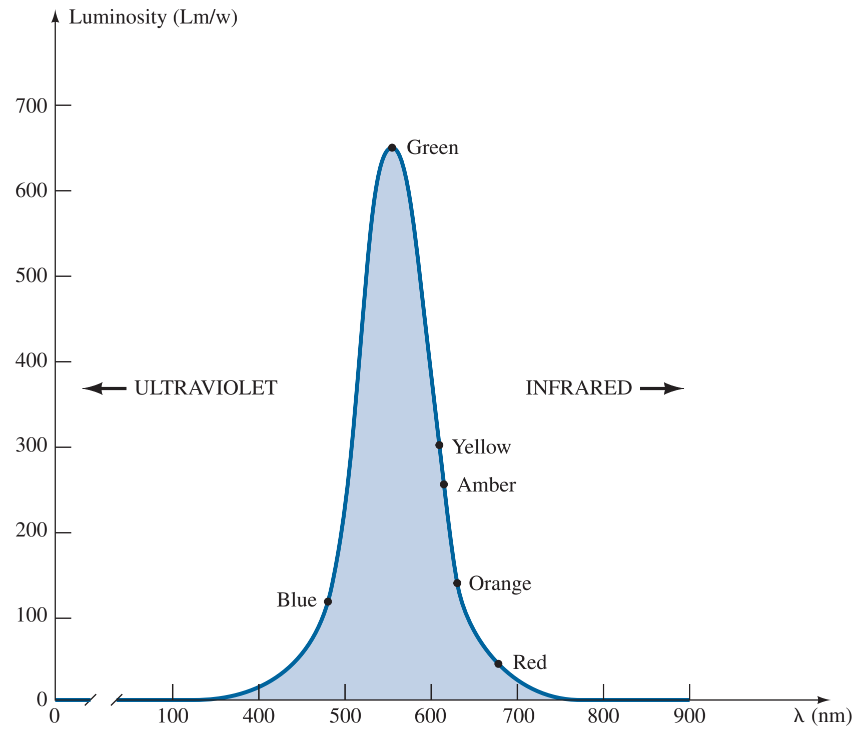


FIG. 51

Standard response curve of the human eye, showing the eye's response to light energy peaks at green and falls off for blue and red.

In Section 4 it was mentioned briefly that GaAs with its higher energy gap of 1.43 eV made it suitable for electromagnetic radiation of visible light, whereas Si at 1.1 eV resulted primarily in heat dissipation on recombination. The effect of this difference in energy gaps can be explained to some degree by realizing that to move an electron from one discrete energy level to another requires a specific amount of energy. The amount of energy involved is given by

$$\boxed{E_g = \frac{hc}{\lambda}} \tag{16}$$

with E_g = joules (J) [1 eV = 1.6×10^{-19} J]
h = Planck's constant = 6.626×10^{-34} J • s.
$c = 3 \times 10^8$ m/s
λ = wavelength in meters

If we substitute the energy gap level of 1.43 eV for GaAs into the equation, we obtain the following wavelength:

$$1.43\ \cancel{\text{eV}}\left[\frac{1.6 \times 10^{-19}\ \text{J}}{1\ \cancel{\text{eV}}}\right] = 2.288 \times 10^{-19}\ \text{J}$$

and

$$\lambda = \frac{hc}{E_g} = \frac{(6.626 \times 10^{-34}\ \text{J} \cdot \text{s})(3 \times 10^8\ \text{m/s})}{2.288 \times 10^{-19}\ \text{J}}$$
$$= 869\ \mathbf{nm}$$

For silicon, with $E_g = 1.1$ eV

$$\lambda = \mathbf{1130\ nm}$$

which is well beyond the visible range of Fig. 51.

The wavelength of 869 nm places GaAs in the wavelength zone typically used in infrared devices. For a compound material such as GaAsP with a band gap of 1.9 eV the resulting wavelength is 654 nm, which is in the center of the red zone, making it an excellent compound semiconductor for LED production. In general, therefore:

The wavelength and frequency of light of a specific color are directly related to the energy band gap of the material.

A first step, therefore, in the production of a compound semiconductor that can be used to generate light is to come up with a combination of elements that will generate the desired energy band gap.

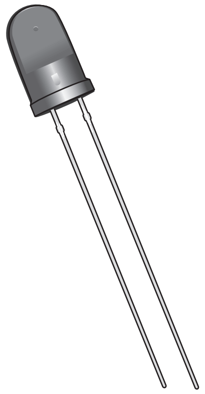
The appearance and characteristics of a subminiature high-efficiency red LED manufactured by Hewlett-Packard are given in Fig. 52. Note in Fig. 52b that the peak forward current is 60 mA, with 20 mA the typical average forward current. The text conditions listed in Fig. 52c, however, are for a forward current of 10 mA. The level of V_D under forward-bias conditions is listed as V_F and extends from 2.2 V to 3 V. In other words, one can expect a typical operating current of about 10 mA at 2.3 V for good light emission, as shown in Fig. 52e. In particular, note the typical diode characteristics for an LED.

Two quantities yet undefined appear under the heading Electrical/Optical Characteristics at $T_A = 25°\text{C}$. They are the *axial luminous intensity* (I_V) and the *luminous efficacy* (η_V). Light intensity is measured in *candelas.* One candela (cd) corresponds to a light flux of 4π lumens (lm) and is equivalent to an illumination of *1 footcandle* on a 1-ft^2 area 1 ft from the light source. Even if this description may not provide a clear understanding of the candela as a unit of measure, it should be enough to allow its level to be compared between similar devices. Figure 52f is a normalized plot of the relative luminous intensity versus forward current. The term *normalized* is used frequently on graphs to give comparisons of response to a particular level.

A normalized plot is one where the variable of interest is plotted with a specific level defined as the reference value with a magnitude of one.

In Fig. 52f the normalized level is taken at $I_F = 10$ mA. Note that the relative luminous intensity is 1 at $I_F = 10$ mA. The graph quickly reveals that the intensity of the light is almost doubled at a current of 15 mA and is almost three times as much at a current of 20 mA. It is important to therefore note that:

The light intensity of an LED will increase with forward current until a point of saturation arrives where any further increase in current will not effectively increase the level of illumination.



(a)

Absolute Maximum Ratings at T_A = 25°C		
Parameter	*High-Efficiency Red 4160*	*Units*
Power dissipation	120	mW
Average forward current	20[1]	mA
Peak forward current	60	mA
Operating and storage temperature range	−55°C to 100°C	
Lead soldering temperature [1.6 mm (0.063 in.) from body]	230°C for 3 s	

NOTE: 1. Derate from 50°C at 0.2 mV/°C.

(b)

Electrical/Optical Characteristics at T_A = 25°C

Symbol	*Description*	*High-Efficiency Red 4160 Min.*	*Typ.*	*Max.*	*Units*	*Test Conditions*
						I_F = 10 mA
I_V	Axial luminous intensity	1.0	3.0		mcd	
$2\theta_{1/2}$	Included angle between half luminous intensity points		80		degree	Note 1
λ_{peak}	Peak wavelength		635		nm	Measurement at peak
λ_d	Dominant wavelength		628		nm	Note 2
τ_s	Speed of response		90		ns	
C	Capacitance		11		pF	$V_F = 0$; $f = 1$ Mhz
θ_{JC}	Thermal resistance		120		°C/W	Junction to cathode lead at 0.79 mm (0.031 in.) from body
V_F	Forward voltage		2.2	3.0	V	I_F = 10 mA
BV_R	Reverse breakdown voltage	5.0			V	I_R = 100 μA
η_v	Luminous efficacy		147		lm/W	Note 3

NOTES:
1. $\theta_{1/2}$ is the off-axis angle at which the luminous intensity is half the axial luminous intensity.
2. The dominant wavelength, λ_d, is derived from the CIE chromaticity diagram and represents the single wavelength that defines the color of the device.
3. Radiant intensity, I_e, in watts/steradian, may be found from the equation $I_e = I_v/\eta_v$, where I_v is the luminous intensity in candelas and η_v is the luminous efficacy in lumens/watt.

(c)

FIG. 52

Hewlett-Packard subminiature high-efficiency red solid-state lamp: (a) appearance; (b) absolute maximum ratings; (c) electrical/optical characteristics; (d) relative intensity versus wavelength; (e) forward current versus forward voltage; (f) relative luminous intensity versus forward current; (g) relative efficiency versus peak current; (h) relative luminous intensity versus angular displacement.

For instance, note in Fig. 52g that the increase in relative efficiency starts to level off as the current exceeds 50 mA.

The term *efficacy* is, by definition, a measure of the ability of a device to produce the desired effect. For the LED this is the ratio of the number of lumens generated per applied watt of electrical power.

The plot of Fig. 52d supports the information appearing on the eye-response curve of Fig. 51. As indicated above, note the bell-shaped curve for the range of wavelengths that will result in each color. The peak value of this device is near 630 nm, very close to the peak value of the GaAsP red LED. The curves of green and yellow are only provided for reference purposes.

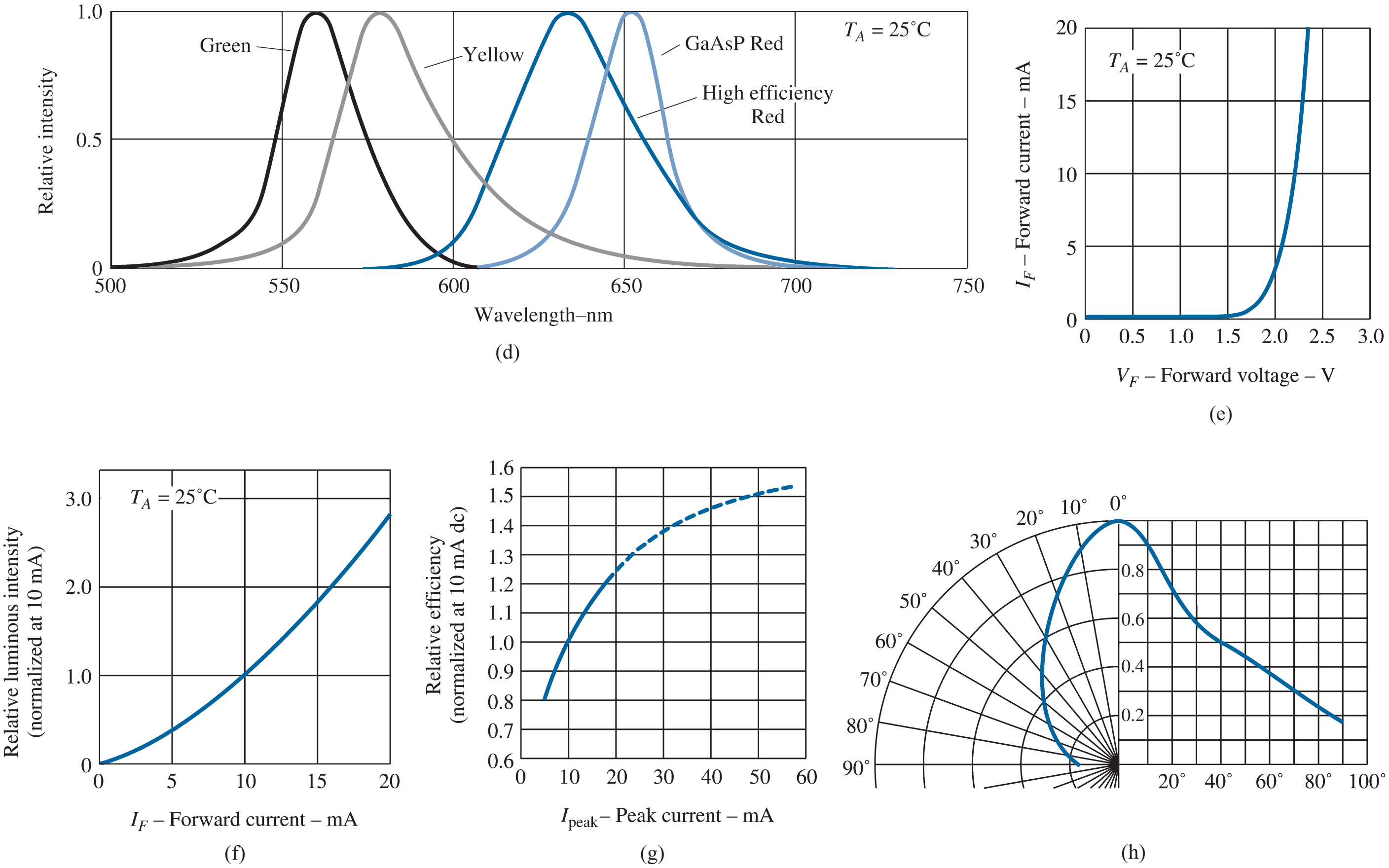


FIG. 52
Continued.

Figure 52h is a graph of light intensity versus angle measured from 0° (head on) to 90° (side view). Note that at 40° the intensity has already dropped to 50% of the head-on intensity.

One of the major concerns when using an LED is the reverse-bias breakdown voltage, which is typically between 3 V and 5 V (an occasional device has a 10-V level).

This range of values is significantly less than that of a standard commercial diode, where it can extend to thousands of volts. As a result one has to be acutely aware of this severe limitation in the design process.

In the analysis and design of networks with LEDs it is helpful to have some idea of the voltage and current levels to be expected.

For many years the only colors available were green, yellow, orange, and red, permitting the use of the average values of $V_F = 2$ V and $I_F = 20$ mA for obtaining an approximate operating level.

However, with the introduction of blue in the early 1990s and white in the late 1990s the magnitude of these two parameters has changed. For blue the average forward bias voltage can be as high as 5 V, and for white about 4.1 V, although both have a typical operating current of 20 mA or more. In general, therefore:

Assume an average forward-bias voltage of 5 V for blue and 4 V for white LEDs at currents of 20 mA to initiate an analysis of networks with these types of LEDs.

Every once in a while a device is introduced that seems to open the door to a slue of possibilities. Such is the case with the introduction of white LEDs. The slow start for white LEDs is primarily due to the fact that it is not a primary color like green, blue, and red. Every other color that one requires, such as on a TV screen, can be generated from these three colors (as in virtually all monitors available today). Yes, the right combination of these three colors can give white—hard to believe, but it works. The best evidence is the human eye, which only has cones sensitive to red, green, and blue. The brain is responsible for processing the input and perceiving the "white" light and color we see in our everyday lives. The same reasoning was used to generate some of the first white LEDs, by combining the right proportions of a red, a green, and a blue LED in a single package. Today, however, most white LEDs are constructed of a blue *gallium nitride* LED below a film *of yttrium-aluminum garnet* (YAG) phosphor. When the blue light hits the phosphor, a yellow light is generated. The mix of this yellow emission with that of the central blue LED forms a white light—incredible, but true.

Since most of the lighting for homes and offices is white light, we now have another option to consider versus incandescent and fluorescent lighting. The rugged characteristics of LED white light along with lifetimes that exceed 25,000 hours, clearly suggest that this will be a true competitor in the near future. Various companies are now providing replacement LED bulbs for almost every possible application. Some have efficacy ratings as high as 135.7 lumens per watt, far exceeding the 25 lumens per watt of a few years ago. It is forecast that 7 W of power will soon be able to generate 1,000 lm of light, which exceeds the illumination of a 60 W bulb and can run off four D cell batteries. Imagine the same lighting with less than 1/8 the power requirement. At the present time entire offices, malls, street lighting, sporting facilities, and so on are being designed using solely LED lighting. Recently, LEDs are the common choice for flashlights and many high-end automobiles due to the sharp intensity at lower dc power requirements. The tube light of Fig. 53a replaces the standard fluorescent bulb typically found in the ceiling fixtures of both the home and industry. Not only do they draw 20% less energy while providing 25% additional light but they also last twice as long as a standard fluorescent bulb. The flood light of Fig. 53b draws 1.7 watts for each 140 lumens of light resulting in an enormous 90% savings in energy compared to the incandescent variety. The chandelier bulbs of Fig. 53c have a lifetime of 50,000 hours and only draw 3 watts of power while generating 200 lumens of light.

FIG. 53
LED residential and commercial lighting.

Before leaving the subject, let us look at a seven-segment digital display housed in a typical dual in-line integrated circuit package as shown in Fig. 54. By energizing the proper pins with a typical 5-V dc level, a number of the LEDs can be energized and the desired numeral displayed. In Fig. 54a the pins are defined by looking at the face of the display and counting counterclockwise from the top left pin. Most seven-segment displays are either common-anode or common-cathode displays, with the term *anode* referring to the defined positive side of each diode and the *cathode* referring to the negative side. For the common-cathode option the pins have the functions listed in Fig. 54b and appear as in Fig. 54c. In the common-cathode configuration all the cathodes are connected together to form a common point for the negative side of each LED. Any LED with a positive 5 V applied to the anode or numerically numbered pin side will turn on and produce light for that segment. In Fig. 54c, 5 V has been applied to the terminals that generate the numeral 5. For this particular unit the average forward turn-on voltage is 2.1 V at a current of 10 mA.

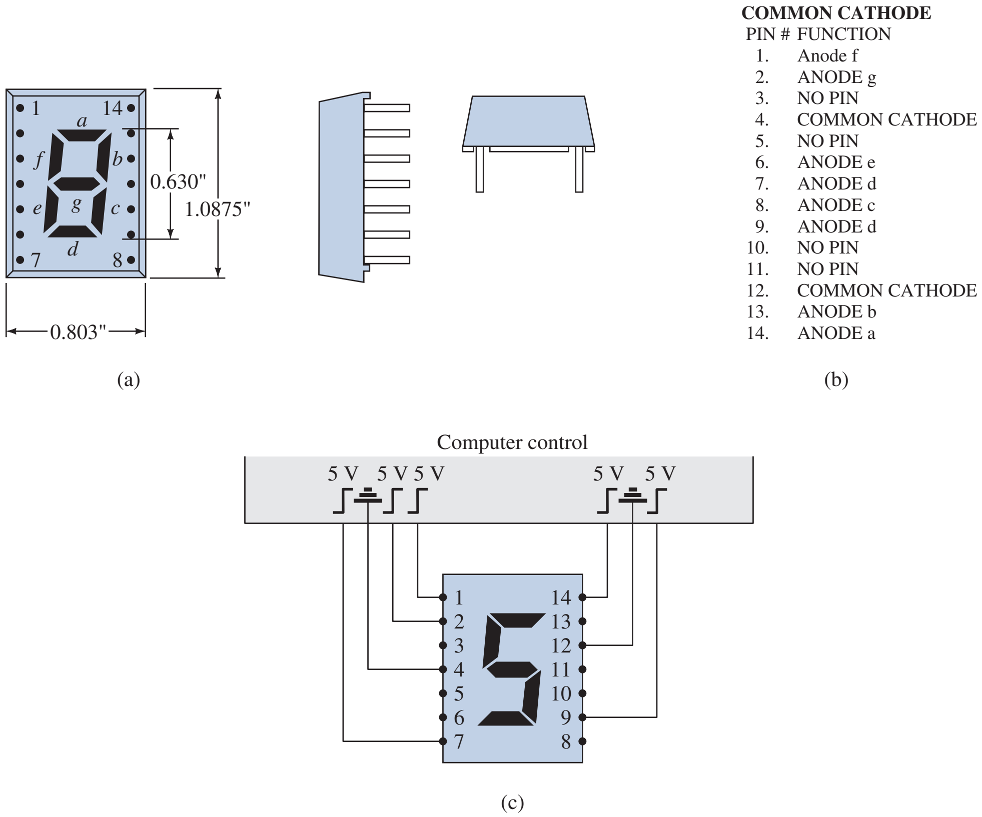


FIG. 54
Seven-segment display: (a) face with pin idenfication; (b) pin function; (c) displaying the numeral 5.

17 SUMMARY

Important Conclusions and Concepts

1. The characteristics of an ideal diode are a close match with those of a **simple switch** except for the important fact that an ideal diode can **conduct in only one direction**.
2. The ideal diode is a **short** in the region of conduction and an **open circuit** in the region of nonconduction.
3. A semiconductor is a material that has a conductivity level somewhere **between** that of a good conductor and that of an insulator.
4. A bonding of atoms, strengthened by the **sharing of electrons** between neighboring atoms, is called covalent bonding.
5. Increasing temperatures can cause a **significant increase** in the number of free electrons in a semiconductor material.
6. Most semiconductor materials used in the electronics industry have **negative temperature coefficients**; that is, the resistance drops with an increase in temperature.
7. Intrinsic materials are those semiconductors that have a very **low level of impurities**, whereas extrinsic materials are semiconductors that have been **exposed to a doping process**.
8. An *n*-type material is formed by adding **donor** atoms that have **five** valence electrons to establish a high level of relatively free electrons. In an *n*-type material, the **electron is the majority carrier** and the hole is the minority carrier.
9. A *p*-type material is formed by adding **acceptor** atoms with **three** valence electrons to establish a high level of holes in the material. In a *p*-type material, the hole is the majority carrier and the electron is the minority carrier.
10. The region near the junction of a diode that has very few carriers is called the **depletion** region.
11. In the **absence** of any externally applied bias, the diode current is zero.
12. In the forward-bias region the diode current **increases exponentially** with increase in voltage across the diode.

13. In the reverse-bias region the diode current is the **very small reverse saturation current** until Zener breakdown is reached and current will flow in the opposite direction through the diode.
14. The reverse saturation current I_s will just about **double** in magnitude for every 10-fold increase in temperature.
15. The dc resistance of a diode is determined by the **ratio** of the diode voltage and current at the point of interest and is **not sensitive** to the shape of the curve. The dc resistance **decreases** with increase in diode current or voltage.
16. The ac resistance of a diode is sensitive to the shape of the curve in the region of interest and decreases for higher levels of diode current or voltage.
17. The threshold voltage is about **0.7 V** for silicon diodes and **0.3 V** for germanium diodes.
18. The maximum power dissipation level of a diode is equal to the **product** of the diode voltage and current.
19. The capacitance of a diode **increases exponentially** with increase in the forward-bias voltage. Its lowest levels are in the reverse-bias region.
20. The direction of conduction for a Zener diode is **opposite** to that of the arrow in the symbol, and the Zener voltage has a polarity opposite to that of a forward-biased diode.
21. Light emitting diodes (LEDs) emit light under **forward-bias conditions** but require 2 V to 4 V for good emission.

Equations

$$I_D = I_s(e^{V_D/nV_T} - 1) \qquad V_T = \frac{kT}{q} \qquad T_K = T_C + 273° \qquad k = 1.38 \times 10^{-23}\ \text{J/K}$$

$$V_K \cong 0.7\ \text{V (Si)}$$

$$V_K \cong 1.2\ \text{V (GaAs)}$$

$$V_K \cong 0.3\ \text{V (Ge)}$$

$$R_D = \frac{V_D}{I_D}$$

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{26\ \text{mV}}{I_D}$$

$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}}$$

$$P_{D_{\max}} = V_D I_D$$

18 COMPUTER ANALYSIS

Two software packages designed to analyze electronic circuits will be introduced and applied throughout the text. They include **Cadence OrCAD, version 16.3** (Fig. 55), and **Multisim, version 11.0.1** (Fig. 56). The content was written with sufficient detail to ensure that the reader will not need to reference any other computer literature to apply both programs.

FIG. 55
Cadence OrCAD Design package version 16.3.
(Photo by Dan Trudden/Pearson.)

FIG. 56
Multisim 11.0.1.
(Photo by Dan Trudden/Pearson.)

Those of you who have used either program in the past will find that the changes are minor and appear primarily in the front end and in the generation of specific data and plots.

The reason for including two programs stems from the fact that both are used throughout the educational community. You will find that the OrCAD software has a broader area of investigation but the Multisim software generates displays that are a better match to the actual laboratory experience.

The demo version of OrCAD is free from Cadence Design Systems, Inc., and can be downloaded directly from the EMA Design Automation, Inc., web site, **info@emaeda.com**. Multisim must be purchased from the **National Instruments Corporation** using their web site, **ni.com/multisim**.

In the past, the OrCAD package was referred to as a **PSpice** program primarily because it is a subset of a more sophisticated version used extensively in industry called **SPICE**. The result is the use of the term PSpice in the descriptions to follow when initiating an analysis using the OrCAD software.

The downloading process for each software package will now be introduced along with the general appearance of the resulting screen.

OrCAD

Installation:

Insert the **OrCAD Release 16.3** DVD into the disk drive to open the **Cadence OrCAD 16.3** software screen.

Select **Demo Installation** and the **Preparing Setup** dialog box will open, followed by the message **Welcome to the Installation Wizard for OrCAD 16.3 Demo**. Select **Next**, and the **License Agreement** dialog box opens. Choose **I accept** and select **Next**, and the **Choose Destination** dialog box will open with **Install OrCAD 16.3 Demo Accept C:\OrCAD\OrCAD_16.3 Demo.**

Select **Next**, and the **Start Copying Files** dialog box opens. Choose **Select** again, and the **Ready to Install Program** dialog box opens. Click **Install**, and the **Installing Crystal Report Xii** box will appear. The **Setup** dialog box opens with the prompt: **Setup status installs program**. The **Install Wizard** is now installing the OrCAD 16.3 Demo.

At completion, a message will appear: **Searching for and adding programs to the Windows firewall exception list. Generating indexes for Cadence Help. This may take some time.**

When the process has completed, select **Finish** and the **Cadence OrCAD 16.3** screen will appear. The software has been installed.

Screen Icon: The screen icon can be established (if it does not appear automatically) by applying the following sequence. **START-All Programs-Cadence-OrCAD 16.3 Demo-OrCAD Capture CIS Demo**, followed by a right-click of the mouse to obtain a listing where **Send to** is chosen, followed by **Desktop (create shortcut)**. The OrCAD icon will then appear on the screen and can be moved to the appropriate location.

Folder Creation: Starting with the OrCAD opening screen, right-click on the **Start** option at the bottom left of the screen. Then choose **Explore** followed by **Hard Drive (C:)**. Then place the mouse on the folder listing, and a right-click will result in a listing in which **New** is an option. Choose **New** followed by **Folder**, and then type in **OrCAD 11.3** in the provided area of the screen, followed by a right-click of the mouse. A location for all the files generated using OrCAD has now been established.

Multisim

Installation:

Insert the Multisim disk into the DVD disk drive to obtain the **Autoplay** dialog box.

Then select **Always do this for software and games**, followed by the selection of **Auto-run** to open the **NI Circuit Design Suite 11.0** dialog box.

Enter the full name to be used and provide the serial number. (The serial number appears in the Certificate of Ownership document that came with the NI Circuit Design Suite packet.)

Selecting **Next** will result in the **Destination Directory** dialog box from which one will **Accept** the following: **C:\Program Files(X86) National Instruments**. Select **Next** to open the **Features** dialog box and then select **NI Circuit Design Suite 11.0.1 Education.**

Selecting **Next** will result in the **Product Notification** dialog box with a succeeding **Next** resulting in the **License Agreement** dialog box. A left-click of the mouse on **I accept** can then be followed by choosing **Next** to obtain the **Start Installation** dialog box. Another left-click and the installation process begins, with the progress being displayed. The process takes between 15 and 20 minutes.

At the conclusion of the installation, you will be asked to install the **NI Elvismx driver DVD**. This time **Cancel** will be selected, and the **NI Circuit Design Suite 11.0.1** dialog box will appear with the following message: **NI Circuit Design Suite 11.0.1 has been installed.** Click **Finish**, and the response will be to restart the computer to complete the operation. Select **Restart**, and the computer will shut down and start up again, followed by the appearance of the **Multisim Screen** dialog box.

Select **Activate** and then **Activate through secure Internet connection**, and the **Activation Wizard** dialog box will open. Enter the **serial number** followed by **Next** to enter all the information into the **NI Activation Wizard** dialog box. Selecting **Next** will result in the option of **Send me an email confirmation of this activation**. Select this option and the message **Product successfully activated** will appear. Selecting **Finish** will complete the process.

Screen Icon: The process described for the OrCAD program will produce the same results for Multisim.

Folder Creation: Following the procedure introduced above for the OrCAD program, a folder labeled OrCAD 16.3 was established for the Multisim files.

PROBLEMS

**Note:* Asterisks indicate more difficult problems.

3 Covalent Bonding and Intrinsic Materials

1. Sketch the atomic structure of copper and discuss why it is a good conductor and how its structure is different from that of germanium, silicon, and gallium arsenide.
2. In your own words, define an intrinsic material, a negative temperature coefficient, and covalent bonding.
3. Consult your reference library and list three materials that have a negative temperature coefficient and three that have a positive temperature coefficient.

4 Energy Levels

4. **a.** How much energy in joules is required to move a charge of 12 μC through a difference in potential of 6 V?
   b. For part (a), find the energy in electron-volts.
5. If 48 eV of energy is required to move a charge through a potential difference of 3.2 V, determine the charge involved.
6. Consult your reference library and determine the level of E_g for GaP, ZnS, and GaAsP, three semiconductor materials of practical value. In addition, determine the written name for each material.

5 *n*-Type and *p*-Type Materials

7. Describe the difference between *n*-type and *p*-type semiconductor materials.
8. Describe the difference between donor and acceptor impurities.
9. Describe the difference between majority and minority carriers.

10. Sketch the atomic structure of silicon and insert an impurity of arsenic as demonstrated for silicon in Fig. 7.

11. Repeat Problem 10, but insert an impurity of indium.

12. Consult your reference library and find another explanation of hole versus electron flow. Using both descriptions, describe in your own words the process of hole conduction.

6 Semiconductor Diode

13. Describe in your own words the conditions established by forward- and reverse-bias conditions on a *p–n* junction diode and how the resulting current is affected.

14. Describe how you will remember the forward- and reverse-bias states of the *p–n* junction diode. That is, how will you remember which potential (positive or negative) is applied to which terminal?

15. **a.** Determine the thermal voltage for a diode at a temperature of 20°C.
b. For the same diode of part (a), find the diode current using Eq. 2 if $I_s = 40$ nA, $n = 2$ (low value of V_D), and the applied bias voltage is 0.5 V.

16. Repeat Problem 15 for $T = 100°$C (boiling point of water). Assume that I_s has increased to 5.0 μA.

17. **a.** Using Eq. (2), determine the diode current at 20°C for a silicon diode with $n = 2$, $I_s = 0.1$ μA at a reverse-bias potential of -10 V.
b. Is the result expected? Why?

18. Given a diode current of 8 mA and $n = 1$, find I_s if the applied voltage is 0.5 V and the temperature is room temperature (25°C).

***19.** Given a diode current of 6 mA, $V_T = 26$ mV, $n = 1$, and $I_s = 1$ nA, find the applied voltage V_D.

20. **a.** Plot the function $y = e^x$ for x from 0 to 10. Why is it difficult to plot?
b. What is the value of $y = e^x$ at $x = 0$?
c. Based on the results of part (b), why is the factor -1 important in Eq. (2)?

21. In the reverse-bias region the saturation current of a silicon diode is about 0.1 μA ($T = 20°$C). Determine its approximate value if the temperature is increased 40°C.

22. Compare the characteristics of a silicon and a germanium diode and determine which you would prefer to use for most practical applications. Give some details. Refer to a manufacturer's listing and compare the characteristics of a germanium and a silicon diode of similar maximum ratings.

23. Determine the forward voltage drop across the diode whose characteristics appear in Fig. 19 at temperatures of -75°C, 25°C, 125°C and a current of 10 mA. For each temperature, determine the level of saturation current. Compare the extremes of each and comment on the ratio of the two.

7 Ideal versus Practical

24. Describe in your own words the meaning of the word *ideal* as applied to a device or a system.

25. Describe in your own words the characteristics of the *ideal* diode and how they determine the on and off states of the device. That is, describe why the short-circuit and open-circuit equivalents are appropriate.

26. What is the one important difference between the characteristics of a simple switch and those of an ideal diode?

8 Resistance Levels

27. Determine the static or dc resistance of the commercially available diode of Fig. 15 at a forward current of 4 mA.

28. Repeat Problem 27 at a forward current of 15 mA and compare results.

29. Determine the static or dc resistance of the commercially available diode of Fig. 15 at a reverse voltage of -10 V. How does it compare to the value determined at a reverse voltage of -30 V?

30. Calculate the dc and ac resistances for the diode of Fig. 15 at a forward current of 10 mA and compare their magnitudes.

31. **a.** Determine the dynamic (ac) resistance of the commercially available diode of Fig. 15 at a forward current of 10 mA using Eq. (5).
b. Determine the dynamic (ac) resistance of the diode of Fig. 15 at a forward current of 10 mA using Eq. (6).
c. Compare solutions of parts (a) and (b).

32. Using Eq. (5), determine the ac resistance at a current of 1 mA and 15 mA for the diode of Fig. 15. Compare the solutions and develop a general conclusion regarding the ac resistance and increasing levels of diode current.

33. Using Eq. (6), determine the ac resistance at a current of 1 mA and 15 mA for the diode of Fig. 15. Modify the equation as necessary for low levels of diode current. Compare to the solutions obtained in Problem 32.

34. Determine the average ac resistance for the diode of Fig. 15 for the region between 0.6 V and 0.9 V.

35. Determine the ac resistance for the diode of Fig. 15 at 0.75 V and compare it to the average ac resistance obtained in Problem 34.

9 Diode Equivalent Circuits

36. Find the piecewise-linear equivalent circuit for the diode of Fig. 15. Use a straight-line segment that intersects the horizontal axis at 0.7 V and best approximates the curve for the region greater than 0.7 V.

37. Repeat Problem 36 for the diode of Fig. 27.

38. Find the piecewise-linear equivalent circuit for the germanium and gallium arsenide diodes of Fig. 18.

10 Transition and Diffusion Capacitance

***39.** **a.** Referring to Fig. 33, determine the transition capacitance at reverse-bias potentials of -25 V and -10 V. What is the ratio of the change in capacitance to the change in voltage?

b. Repeat part (a) for reverse-bias potentials of -10 V and -1 V. Determine the ratio of the change in capacitance to the change in voltage.

c. How do the ratios determined in parts (a) and (b) compare? What does this tell you about which range may have more areas of practical application?

40. Referring to Fig. 33, determine the diffusion capacitance at 0 V and 0.25 V.

41. Describe in your own words how diffusion and transition capacitances differ.

42. Determine the reactance offered by a diode described by the characteristics of Fig. 33 at a forward potential of 0.2 V and a reverse potential of -20 V if the applied frequency is 6 MHz.

43. The no-bias transition capacitance of a silicon diode is 8 pF with $V_K = 0.7$ V and $n = 1/2$. What is the transition capacitance if the applied reverse bias potential is 5 V?

44. Find the applied reverse bias potential if the transition capacitance of a silicon diode is 4 pF but the no-bias level is 10 pF with $n = 1/3$ and $V_K = 0.7$ V.

11 Reverse Recovery Time

45. Sketch the waveform for i of the network of Fig. 57 if $t_t = 2t_s$ and the total reverse recovery time is 9 ns.

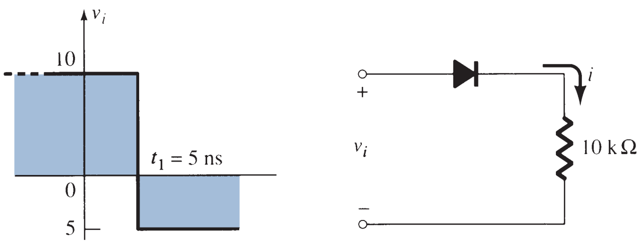


FIG. 57
Problem 45.

12 Diode Specification Sheets

***46.** Plot I_F versus V_F using linear scales for the diode of Fig. 37. Note that the provided graph employs a log scale for the vertical axis.

47. **a.** Comment on the change in capacitance level with increase in reverse-bias potential for the diode of Fig. 37.

b. What is the level of $C(0)$?

c. Using $V_K = 0.7$ V, find the level of n in Eq. 9.

48. Does the reverse saturation current of the diode of Fig. 37 change significantly in magnitude for reverse-bias potentials in the range -25 V to -100 V?

***49.** For the diode of Fig. 37 determine the level of I_R at room temperature (25°C) and the boiling point of water (100°C). Is the change significant? Does the level just about double for every 10°C increase in temperature?

50. For the diode of Fig. 37, determine the maximum ac (dynamic) resistance at a forward current of 0.1, 1.5, and 20 mA. Compare levels and comment on whether the results support conclusions derived in earlier sections of this chapter.

51. Using the characteristics of Fig. 37, determine the maximum power dissipation levels for the diode at room temperature (25°C) and 100°C. Assuming that V_F remains fixed at 0.7 V, how has the maximum level of I_F changed between the two temperature levels?

52. Using the characteristics of Fig. 37, determine the temperature at which the diode current will be 50% of its value at room temperature (25°C).

15 Zener Diodes

53. The following characteristics are specified for a particular Zener diode: $V_Z = 29$ V, $V_R = 16.8$ V, $I_{ZT} = 10$ mA, $I_R = 20$ μA, and $I_{ZM} = 40$ mA. Sketch the characteristic curve in the manner displayed in Fig. 47.

***54.** At what temperature will the 10-V Zener diode of Fig. 47 have a nominal voltage of 10.75 V? (*Hint:* Note the data in Table 7.)

55. Determine the temperature coefficient of a 5-V Zener diode (rated 25°C value) if the nominal voltage drops to 4.8 V at a temperature of 100°C.

56. Using the curves of Fig. 48a, what level of temperature coefficient would you expect for a 20-V diode? Repeat for a 5-V diode. Assume a linear scale between nominal voltage levels and a current level of 0.1 mA.

57. Determine the dynamic impedance for the 24-V diode at $I_Z = 10$ mA for Fig. 48b. Note that it is a log scale.

***58.** Compare the levels of dynamic impedance for the 24-V diode of Fig. 48b at current levels of 0.2, 1, and 10 mA. How do the results relate to the shape of the characteristics in this region?

16 Light-Emitting Diodes

59. Referring to Fig. 52e, what would appear to be an appropriate value of V_K for this device? How does it compare to the value of V_K for silicon and germanium?

60. Given that $E_g = 0.67$ eV for germanium, find the wavelength of peak solar response for the material. Do the photons at this wavelength have a lower or higher energy level?

61. Using the information provided in Fig. 52, determine the forward voltage across the diode if the relative luminous intensity is l.5.

***62.** **a.** What is the percentage increase in relative efficiency of the device of Fig. 52 if the peak current is increased from 5 mA to 10 mA?
b. Repeat part (a) for 30 mA to 35 mA (the same increase in current).
c. Compare the percentage increase from parts (a) and (b). At what point on the curve would you say there is little to be gained by further increasing the peak current?

63. **a.** If the luminous intensity at 0° angular displacement is 3.0 mcd for the device of Fig. 52, at what angle will it be 0.75 mcd?
b. At what angle does the loss of luminous intensity drop below the 50% level?

***64.** Sketch the current derating curve for the average forward current of the high-efficiency red LED of Fig. 52 as determined by temperature. (Note the absolute maximum ratings.)

SOLUTIONS TO SELECTED ODD-NUMBERED PROBLEMS

5. 2.4×10^{-18} C
15. **(a)** 25.27 mV **(b)** 11.84 mA
17. **(a)** 25.27 mV **(b)** 0.1 μA
19. 0.41 V
21. 1.6 μA
23. −75°C: 1.1 V, 0.01 pA; 25°C: 0.85 V, 1 pA; 125°C: 1.1 V, 105 μA
27. 175 Ω
29. −10 V: 100 MΩ; −30 V: 300 MΩ
31. **(a)** 3 Ω **(b)** 2.6 Ω **(c)** quite close
33. 1 mA: 52 Ω, 15 mA: 1.73 Ω

35. 22.5 Ω
37. $r_d = 4\ \Omega$
39. **(a)** -25 V: 0.75 pF; -10 V: 1.25 pF; $\Delta C_T/\Delta V_R = 0.033$ pF/V
43. 2.81 pF
45. $t_s = 3$ ns, $t_t = 6$ ns
47. **(b)** 6 pF **(c)** 0.58
49. 25°C: 0.5 nA; 100°C: 60 nA; 60 nA: 0.5 nA = 120:1
51. 25°C: 500 mW; 100°C: 260 mW; 25°C: 714.29 mA; 100°C: 371.43 mA
55. 0.053%/°C
57. 13 Ω
59. 2 V
61. 2.3 V
63. **(a)** 75° **(b)** 40°

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Diode Applications

CHAPTER OBJECTIVES

- Understand the concept of load-line analysis and how it is applied to diode networks.
- Become familiar with the use of equivalent circuits to analyze series, parallel, and series-parallel diode networks.
- Understand the process of rectification to establish a dc level from a sinusoidal ac input.
- Be able to predict the output response of a clipper and clamper diode configuration.
- Become familiar with the analysis of and the range of applications for Zener diodes.

1 INTRODUCTION

This chapter will develop a working knowledge of the diode in a variety of configurations using models appropriate for the area of application. By chapter's end, the fundamental behavior pattern of diodes in dc and ac networks should be clearly understood. For instance, diodes are frequently employed in the description of the basic construction of transistors and in the analysis of transistor networks in the dc and ac domains.

This chapter demonstrates an interesting and very useful aspect of the study of a field such as electronic devices and systems:

Once the basic behavior of a device is understood, its function and response in an infinite variety of configurations can be examined.

In other words, now that we have a basic knowledge of the characteristics of a diode along with its response to applied voltages and currents, we can use this knowledge to examine a wide variety of networks. There is no need to reexamine the response of the device for each application.

In general:

The analysis of electronic circuits can follow one of two paths: using the actual characteristics or applying an approximate model for the device.

For the diode the initial discussion will include the actual characteristics to clearly demonstrate how the characteristics of a device and the network parameters interact. Once there is confidence in the results obtained, the approximate piecewise model will be employed to verify the results found using the complete characteristics. It is important that the role and the response of various elements of an electronic system be understood without continually having to resort to lengthy mathematical procedures. This is usually accomplished through the approximation process, which can develop into an art itself. Although the results obtained using the actual characteristics may be slightly different from those obtained using a series of approximations, keep in mind that the characteristics obtained from a specification sheet may be slightly different from those of the device in actual use. In other words, for example, the characteristics of a 1N4001 semiconductor diode may vary from one element to the next in the same lot. The variation may be slight, but it will often be sufficient to justify the approximations employed in the analysis. Also consider the other elements of the network: Is the resistor labeled 100 Ω exactly 100 Ω? Is the applied voltage exactly 10 V or perhaps 10.08 V? All these tolerances contribute to the general belief that a response determined through an appropriate set of approximations can often be "as accurate" as one that employs the full characteristics. In this text the emphasis is toward developing a working knowledge of a device through the use of appropriate approximations, thereby avoiding an unnecessary level of mathematical complexity. Sufficient detail will normally be provided, however, to permit a detailed mathematical analysis if desired.

2 LOAD-LINE ANALYSIS

The circuit of Fig. 1 is the simplest of diode configurations. It will be used to describe the analysis of a diode circuit using its actual characteristics. In the next section we will replace the characteristics by an approximate model for the diode and compare solutions. Solving the circuit of Fig. 1 is all about finding the current and voltage levels that will satisfy both the characteristics of the diode and the chosen network parameters at the same time.

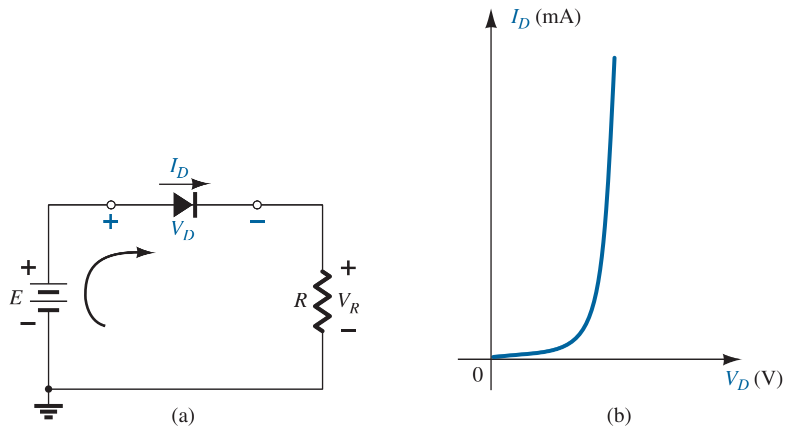


FIG. 1
Series diode configuration: (a) circuit; (b) characteristics.

In Fig. 2 the diode characteristics are placed on the same set of axes as a straight line defined by the parameters of the network. The straight line is called a *load line* because the intersection on the vertical axis is defined by the applied load R. The analysis to follow is therefore called *load-line analysis.* The intersection of the two curves will define the solution for the network and define the current and voltage levels for the network.

Before reviewing the details of drawing the load line on the characteristics, we need to determine the expected response of the simple circuit of Fig. 1. Note in Fig. 1 that the effect of the "pressure" established by the dc supply is to establish a conventional current in the direction indicated by the clockwise arrow. The fact that the direction of this current has the same direction as the arrow in the diode symbol reveals that the diode is in the "on" state and will conduct a high level of current. The polarity of the applied voltage has resulted in a forward-bias situation. With the current direction established, the polarities for the voltage across the diode and resistor can be superimposed. The polarity of V_D and the direction of I_D clearly reveal that the diode is indeed in the forward-bias state, resulting in a voltage across the diode in the neighborhood of 0.7 V and a current on the order of 10 mA or more.

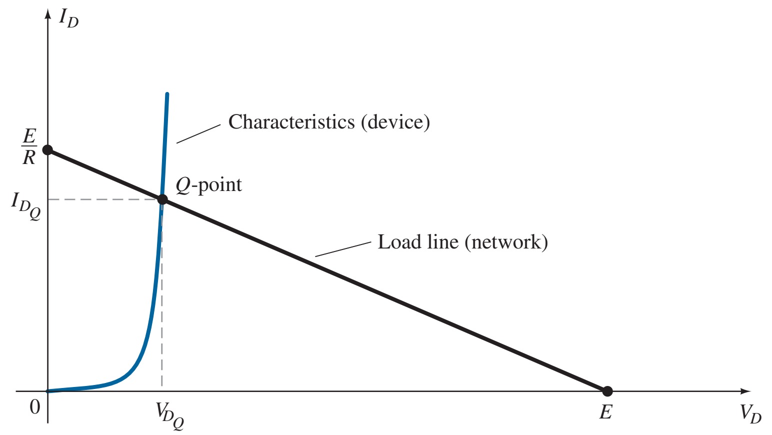


FIG. 2
Drawing the load line and finding the point of operation.

The intersections of the load line on the characteristics of Fig. 2 can be determined by first applying Kirchhoff's voltage law in the clockwise direction, which results in

$$+E - V_D - V_R = 0$$

or

$$\boxed{E = V_D + I_D R} \tag{1}$$

The two variables of Eq. (1), V_D and I_D, are the same as the diode axis variables of Fig. 2. This similarity permits plotting Eq. (1) on the same characteristics of Fig. 2.

The intersections of the load line on the characteristics can easily be determined if one simply employs the fact that anywhere on the horizontal axis $I_D = 0$ A and anywhere on the vertical axis $V_D = 0$ V.

If we *set* $V_D = 0$ V in Eq. (1) and solve for I_D, we have the magnitude of I_D *on* the vertical axis. Therefore, with $V_D = 0$ V, Eq. (1) becomes

$$\begin{aligned} E &= V_D + I_D R \\ &= 0\text{ V} + I_D R \end{aligned}$$

and

$$\boxed{I_D = \frac{E}{R}\bigg|_{V_D = 0\text{ V}}} \tag{2}$$

as shown in Fig. 2. If we *set* $I_D = 0$ A in Eq. (1) and solve for V_D, we have the magnitude of V_D *on* the horizontal axis. Therefore, with $I_D = 0$ A, Eq. (1) becomes

$$\begin{aligned} E &= V_D + I_D R \\ &= V_D + (0\text{ A})R \end{aligned}$$

and

$$\boxed{V_D = E\big|_{I_D = 0\text{ A}}} \tag{3}$$

as shown in Fig. 2. A straight line drawn between the two points will define the load line as depicted in Fig. 2. Change the level of R (the load) and the intersection on the vertical axis will change. The result will be a change in the slope of the load line and a different point of intersection between the load line and the device characteristics.

We now have a load line defined by the network and a characteristic curve defined by the device. The point of intersection between the two is the point of operation for this circuit. By simply drawing a line down to the horizontal axis, we can determine the diode voltage V_{D_Q}, whereas a horizontal line from the point of intersection to the vertical axis will provide the level of I_{D_Q}. The current I_D is actually the current through the entire series configuration of Fig. 1a. The point of operation is usually called the *quiescent point* (abbreviated "*Q*-point") to reflect its "still, unmoving" qualities as defined by a dc network.

The solution obtained at the intersection of the two curves is the same as would be obtained by a simultaneous mathematical solution of

$$I_D = \frac{E}{R} - \frac{V_D}{R} \qquad [\text{derived from Eq. (1)}]$$

and

$$I_D = I_s(e^{V_D/nV_T} - 1)$$

Since the curve for a diode has nonlinear characteristics, the mathematics involved would require the use of nonlinear techniques that are beyond the needs and scope of this text. The load-line analysis described above provides a solution with a minimum of effort and a "pictorial" description of why the levels of solution for V_{D_Q} and I_{D_Q} were obtained. The next example demonstrates the techniques introduced above and reveals the relative ease with which the load line can be drawn using Eqs. (2) and (3).

EXAMPLE 1 For the series diode configuration of Fig. 3a, employing the diode characteristics of Fig. 3b, determine:

a. V_{D_Q} and I_{D_Q}.
b. V_R.

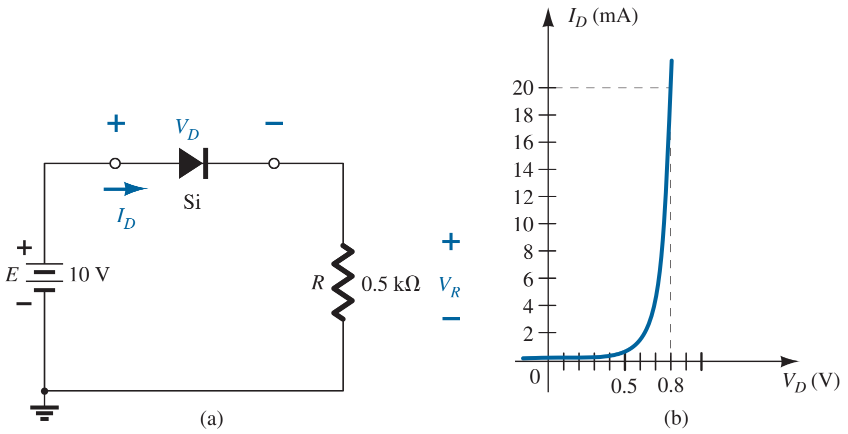


FIG. 3
(a) Circuit; (b) characteristics.

Solution:

a. Eq. (2): $$I_D = \frac{E}{R}\bigg|_{V_D = 0\text{ V}} = \frac{10\text{ V}}{0.5\text{ k}\Omega} = 20\text{ mA}$$

Eq. (3): $$V_D = E\big|_{I_D = 0\text{ A}} = 10\text{ V}$$

The resulting load line appears in Fig. 4. The intersection between the load line and the characteristic curve defines the Q-point as

$$V_{D_Q} \cong \mathbf{0.78\text{ V}}$$
$$I_{D_Q} \cong \mathbf{18.5\text{ mA}}$$

The level of V_D is certainly an estimate, and the accuracy of I_D is limited by the chosen scale. A higher degree of accuracy would require a plot that would be much larger and perhaps unwieldy.

b. $V_R = E - V_D = 10\text{ V} - 0.78\text{ V} = \mathbf{9.22\text{ V}}$

As noted in the example above,

the load line is determined solely by the applied network, whereas the characteristics are defined by the chosen device.

Changing the model we use for the diode will not disturb the network so the load line to be drawn will be exactly the same as appearing in the example above.

Since the network of Example 1 is a dc network the Q-point of Fig. 4 will remain fixed with $V_{D_Q} = 0.78$ V and $I_{D_Q} = 18.5$ mA.

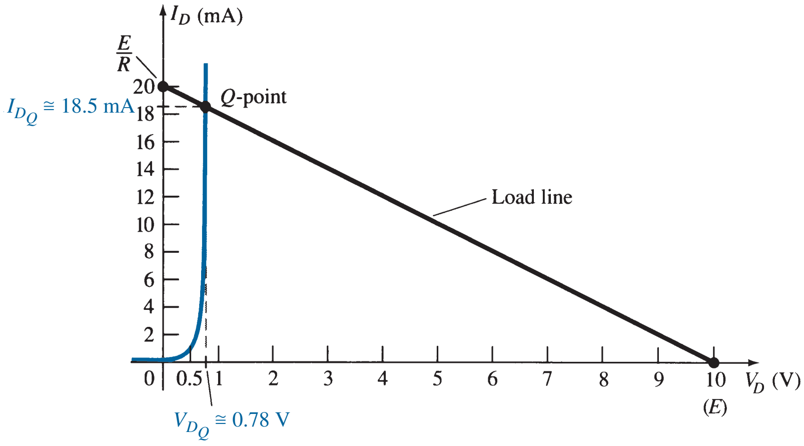


FIG. 4
Solution to Example 1.

Using the Q-point values, the dc resistance for Example 1 is

$$R_D = \frac{V_{D_Q}}{I_{D_Q}} = \frac{0.78\text{ V}}{18.5\text{ mA}} = 42.16\ \Omega$$

An equivalent network (for these operating conditions only) can then be drawn as shown in Fig. 5.

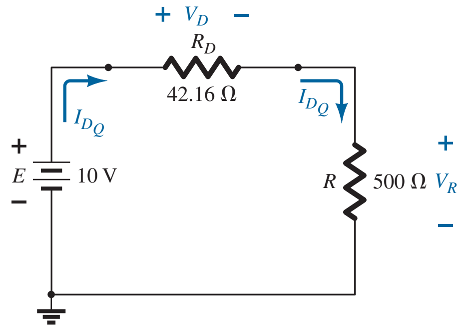


FIG. 5
Network quivalent to Fig. 4.

The current

$$I_D = \frac{E}{R_D + R} = \frac{10\text{ V}}{42.16\ \Omega + 500\ \Omega} = \frac{10\text{ V}}{542.16\ \Omega} \cong \mathbf{18.5\text{ mA}}$$

and
$$V_R = \frac{RE}{R_D + R} = \frac{(500\ \Omega)(10\text{ V})}{42.16\ \Omega + 500\ \Omega} = \mathbf{9.22\text{ V}}$$

matching the results of Example 1.

In essence, therefore, once a dc Q-point has been determined the diode can be replaced by its dc resistance equivalent. This concept of replacing a characteristic by an equivalent model is an important one. Let us now see what effect different equivalent models for the diode will have on the response in Example 1.

EXAMPLE 2 Repeat Example 1 using the approximate equivalent model for the silicon semiconductor diode.

Solution: The load line is redrawn as shown in Fig. 6 with the same intersections as defined in Example 1. The characteristics of the approximate equivalent circuit for the diode have also been sketched on the same graph. The resulting Q-point is

$$V_{D_Q} = \mathbf{0.7\text{ V}}$$
$$I_{D_Q} = \mathbf{18.5\text{ mA}}$$

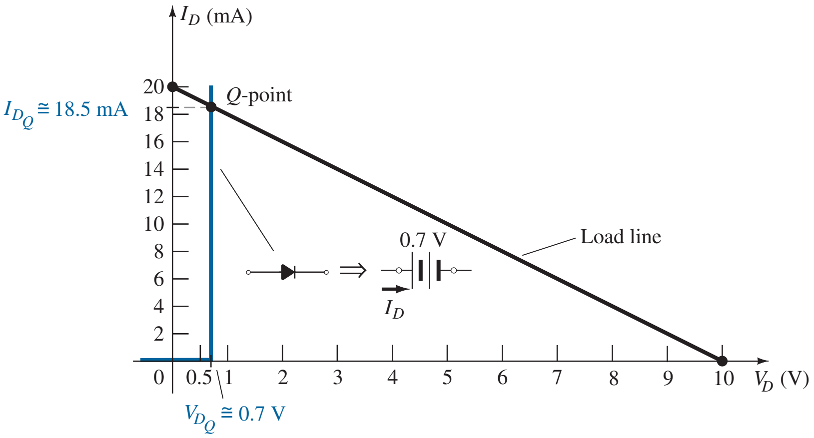


FIG. 6
Solution to Example 1 using the diode approximate model.

The results obtained in Example 2 are quite interesting. The level of I_{D_Q} is exactly the same as obtained in Example 1 using a characteristic curve that is a great deal easier to draw than that appearing in Fig. 4. The $V_D = 0.7$ V here and the 0.78 V from Example 1 are of a different magnitude to the hundredths place, but they are certainly in the same neighborhood if we compare their magnitudes to the magnitudes of the other voltages of the network.

For this situation the dc resistance of the Q-point is

$$R_D = \frac{V_{D_Q}}{I_{D_Q}} = \frac{0.7 \text{ V}}{18.5 \text{ mA}} = 37.84 \, \Omega$$

which is still relatively close to that obtained for the full characteristics.

In the next example we go a step further and substitute the ideal model. The results will reveal the conditions that must be satisfied to apply the ideal equivalent properly.

EXAMPLE 3 Repeat Example 1 using the ideal diode model.

Solution: As shown in Fig. 7, the load line is the same, but the ideal characteristics now intersect the load line on the vertical axis. The Q-point is therefore defined by

$$V_{D_Q} = \mathbf{0 \text{ V}}$$
$$I_{D_Q} = \mathbf{20 \text{ mA}}$$

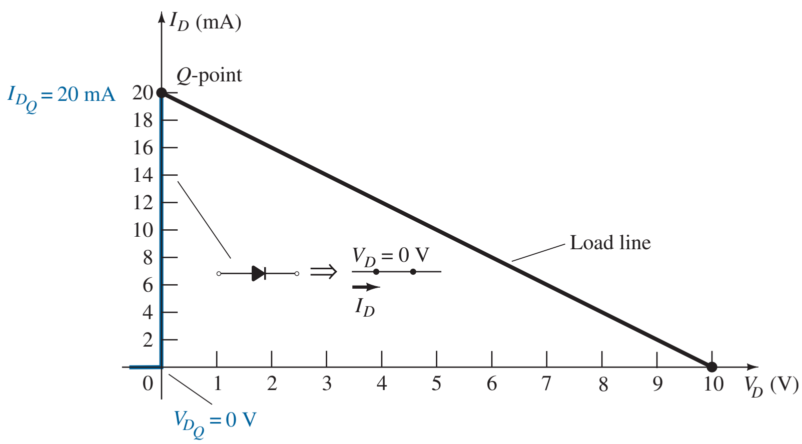


FIG. 7
Solution to Example 1 using the ideal diode model.

The results are sufficiently different from the solutions of Example 1 to cause some concern about their accuracy. Certainly, they do provide some indication of the level of voltage and current to be expected relative to the other voltage levels of the network, but the additional effort of simply including the 0.7-V offset suggests that the approach of Example 2 is more appropriate.

Use of the ideal diode model therefore should be reserved for those occasions when the role of a diode is more important than voltage levels that differ by tenths of a volt and in those situations where the applied voltages are considerably larger than the threshold voltage V_K. In the next few sections the approximate model will be employed exclusively since the voltage levels obtained will be sensitive to variations that approach V_K. In later sections the ideal model will be employed more frequently since the applied voltages will frequently be quite a bit larger than V_K and the authors want to ensure that the role of the diode is correctly and clearly understood.

In this case,

$$R_D = \frac{V_{D_Q}}{I_{D_Q}} = \frac{0\text{ V}}{20\text{ mA}} = 0\ \Omega \text{ (or a short-circuit equivalent)}$$

3 SERIES DIODE CONFIGURATIONS

In the last section we found that the results obtained using the approximate piecewise-linear equivalent model were quite close, if not equal, to the response obtained using the full characteristics. In fact, if one considers all the variations possible due to tolerances, temperature, and so on, one could certainly consider one solution to be "as accurate" as the other. Since the use of the approximate model normally results in a reduced expenditure of time and effort to obtain the desired results, it is the approach that will be employed in this text unless otherwise specified. Recall the following:

The primary purpose of this text is to develop a general knowledge of the behavior, capabilities, and possible areas of application of a device in a manner that will minimize the need for extensive mathematical developments.

For all the analysis to follow in this chapter it is assumed that

The forward resistance of the diode is usually so small compared to the other series elements of the network that it can be ignored.

This is a valid approximation for the vast majority of applications that employ diodes. Using this fact will result in the approximate equivalents for a silicon diode and an ideal diode that appear in Table 1. For the conduction region the only difference between the silicon diode and the ideal diode is the vertical shift in the characteristics, which is accounted for in the equivalent model by a dc supply of 0.7 V opposing the direction of forward current through the device. For voltages less than 0.7 V for a silicon diode and 0 V for the ideal diode the resistance is so high compared to other elements of the network that its equivalent is the open circuit.

For a Ge diode the offset voltage is 0.3 V and for a GaAs diode it is 1.2 V. Otherwise the equivalent networks are the same. For each diode the label Si, Ge, or GaAs will appear along with the diode symbol. For networks with ideal diodes the diode symbol will appear as shown in Table 1 without any labels.

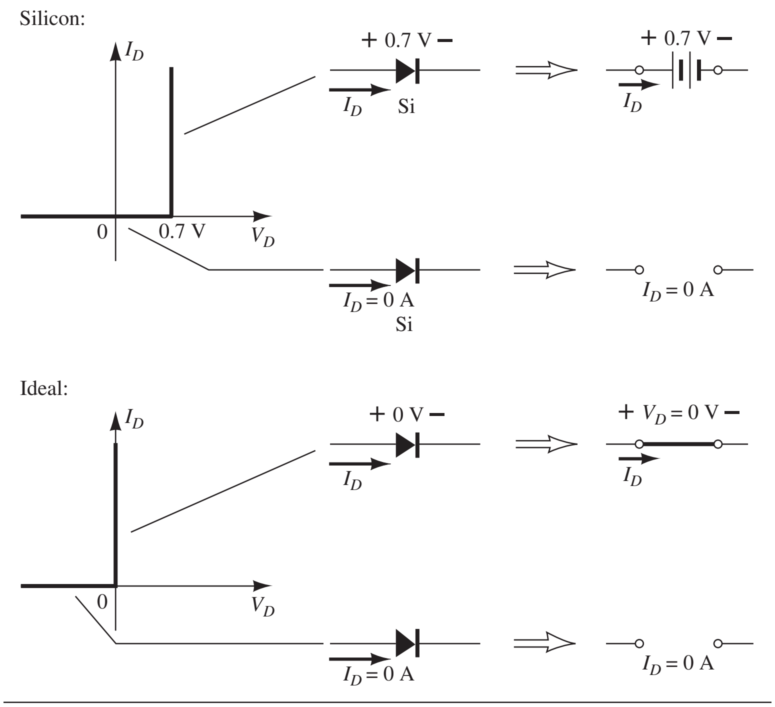
The approximate models will now be used to investigate a number of series diode configurations with dc inputs. This will establish a foundation in diode analysis that will carry over into the sections to follow. The procedure described can, in fact, be applied to networks with any number of diodes in a variety of configurations.

For each configuration the state of each diode must first be determined. Which diodes are "on" and which are "off"? Once determined, the appropriate equivalent can be substituted and the remaining parameters of the network determined.

In general, a diode is in the "on" state if the current established by the applied sources is such that its direction matches that of the arrow in the diode symbol, and $V_D \geq 0.7$ V for silicon, $V_D \geq 0.3$ V for germanium, and $V_D \geq 1.2$ V for gallium arsenide.

For each configuration, *mentally* replace the diodes with resistive elements and note the resulting current direction as established by the applied voltages ("pressure"). If the resulting

TABLE 1
Approximate and Ideal Semiconductor Diode Models.



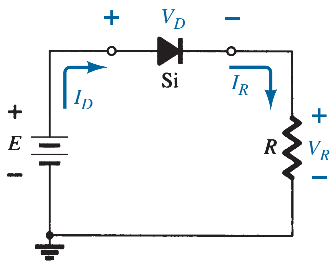


FIG. 8
Series diode configuration.

direction is a "match" with the arrow in the diode symbol, conduction through the diode will occur and the device is in the "on" state. The description above is, of course, contingent on the supply having a voltage greater than the "turn-on" voltage (V_K) of each diode.

If a diode is in the "on" state, one can either place a 0.7-V drop across the element or redraw the network with the V_K equivalent circuit as defined in Table 1. In time the preference will probably simply be to include the 0.7-V drop across each "on" diode and to draw a diagonal line through each diode in the "off" or open state. Initially, however, the substitution method will be used to ensure that the proper voltage and current levels are determined.

The series circuit of Fig. 8 described in some detail in Section 2 will be used to demonstrate the approach described in the above paragraphs. The state of the diode is first determined by mentally replacing the diode with a resistive element as shown in Fig. 9a. The resulting direction of I is a match with the arrow in the diode symbol, and since $E > V_K$, the diode is in the "on" state. The network is then redrawn as shown in Fig. 9b with the appropriate equivalent model for the forward-biased silicon diode. Note for future reference that the polarity of V_D is the same as would result if in fact the diode were a resistive element. The resulting voltage and current levels are the following:

$$\boxed{V_D = V_K} \qquad \textbf{(4)}$$

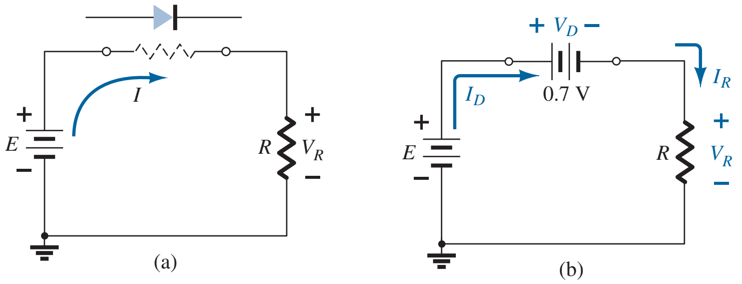


FIG. 9
(a) Determining the state of the diode of Fig. 8; (b) substituting the equivalent model for the "on" diode of Fig. 9a.

$$\boxed{V_R = E - V_K} \tag{5}$$

$$\boxed{I_D = I_R = \frac{V_R}{R}} \tag{6}$$

In Fig. 10 the diode of Fig. 7 has been reversed. Mentally replacing the diode with a resistive element as shown in Fig. 11 will reveal that the resulting current direction does not match the arrow in the diode symbol. The diode is in the "off" state, resulting in the equivalent circuit of Fig. 12. Due to the open circuit, the diode current is 0 A and the voltage across the resistor R is the following:

$$V_R = I_R R = I_D R = (0\text{ A})R = \mathbf{0\ V}$$

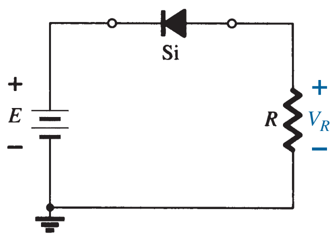


FIG. 10
Reversing the diode of Fig. 8.

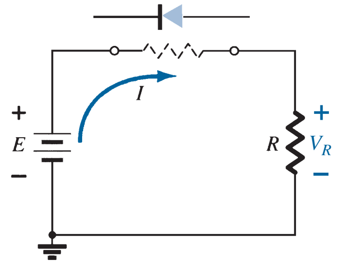


FIG. 11
Determining the state of the diode of Fig. 10.

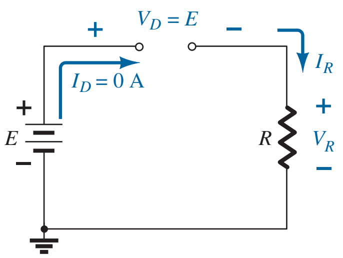


FIG. 12
Substituting the equivalent model for the "off" diode of Fig. 10.

The fact that $V_R = 0$ V will establish E volts across the open circuit as defined by Kirchhoff's voltage law. Always keep in mind that under any circumstances—dc, ac instantaneous values, pulses, and so on—Kirchhoff's voltage law must be satisfied!

EXAMPLE 4 For the series diode configuration of Fig. 13, determine V_D, V_R, and I_D.

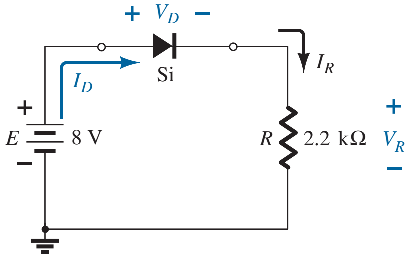


FIG. 13
Circuit for Example 4.

Solution: Since the applied voltage establishes a current in the clockwise direction to match the arrow of the symbol and the diode is in the "on" state,

$$V_D = \mathbf{0.7\ V}$$

$$V_R = E - V_D = 8\text{ V} - 0.7\text{ V} = \mathbf{7.3\ V}$$

$$I_D = I_R = \frac{V_R}{R} = \frac{7.3\text{ V}}{2.2\text{ k}\Omega} \cong \mathbf{3.32\ mA}$$

EXAMPLE 5 Repeat Example 4 with the diode reversed.

Solution: Removing the diode, we find that the direction of I is opposite to the arrow in the diode symbol and the diode equivalent is the open circuit no matter which model is employed. The result is the network of Fig. 14, where $I_D = \mathbf{0\ A}$ due to the open circuit. Since $V_R = I_R R$, we have $V_R = (0)R = \mathbf{0\ V}$. Applying Kirchhoff's voltage law around the closed loop yields

$$E - V_D - V_R = 0$$

and
$$V_D = E - V_R = E - 0 = E = 8\text{ V}$$

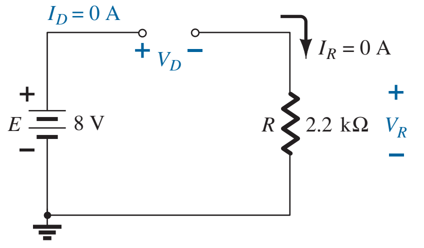


FIG. 14
Determining the unknown quantities for Example 5.

In particular, note in Example 5 the high voltage across the diode even though it is an "off" state. The current is zero, but the voltage is significant. For review purposes, keep the following in mind for the analysis to follow:

An open circuit can have any voltage across its terminals, but the current is always 0 A.

A short circuit has a 0-V drop across its terminals, but the current is limited only by the surrounding network.

In the next example the notation of Fig. 15 will be employed for the applied voltage. It is a common industry notation and one with which the reader should become very familiar.

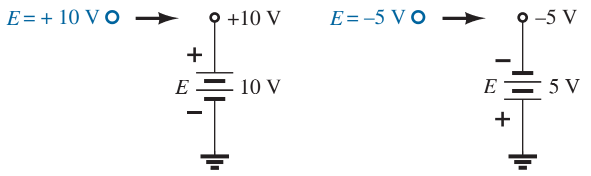


FIG. 15
Source notation.

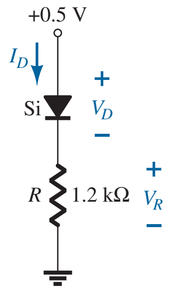


FIG. 16
Series diode circuit for Example 6.

EXAMPLE 6 For the series diode configuration of Fig. 16, determine V_D, V_R, and I_D.

Solution: Although the "pressure" establishes a current with the same direction as the arrow symbol, the level of applied voltage is insufficient to turn the silicon diode "on." The point of operation on the characteristics is shown in Fig. 17, establishing the open-circuit equivalent as the appropriate approximation, as shown in Fig. 18. The resulting voltage and current levels are therefore the following:

$$I_D = \mathbf{0\ A}$$

$$V_R = I_R R = I_D R = (0\text{ A})\,1.2\text{ k}\Omega = \mathbf{0\ V}$$

and
$$V_D = E = \mathbf{0.5\ V}$$

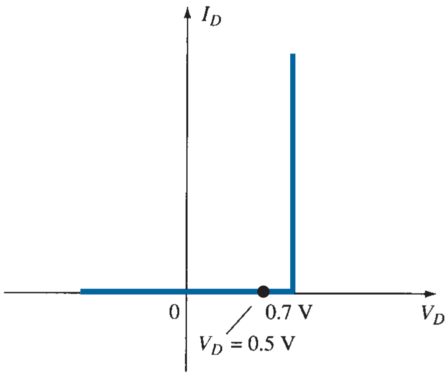


FIG. 17
Operating point with $E = 0.5$ V.

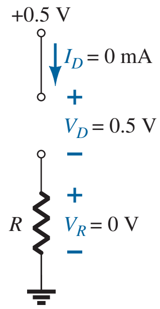


FIG. 18
Determining I_D, V_R, and V_D for the circuit of Fig. 16.

EXAMPLE 7 Determine V_o and I_D for the series circuit of Fig. 19.

Solution: An attack similar to that applied in Example 4 will reveal that the resulting current has the same direction as the arrowheads of the symbols of both diodes, and the network of Fig. 20 results because $E = 12\text{ V} > (0.7\text{ V} + 1.8\text{ V}) = 2.5\text{ V}$. Note the redrawn supply of 12 V and the polarity of V_o across the 680-Ω resistor. The resulting voltage is

$$V_o = E - V_{K_1} - V_{K_2} = 12\text{ V} - 2.5\text{ V} = \mathbf{9.5\text{ V}}$$

and

$$I_D = I_R = \frac{V_R}{R} = \frac{V_o}{R} = \frac{9.5\text{ V}}{680\ \Omega} = \mathbf{13.97\text{ mA}}$$

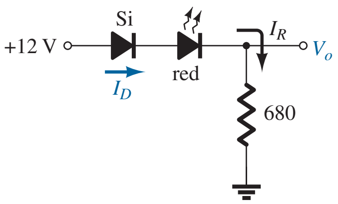


FIG. 19
Circuit for Example 7.

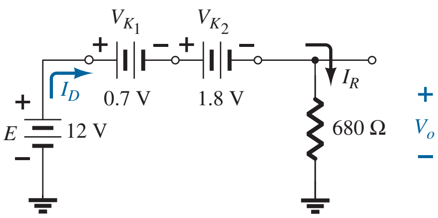


FIG. 20
Determining the unknown quantities for Example 7.

EXAMPLE 8 Determine I_D, V_{D_2}, and V_o for the circuit of Fig. 21.

Solution: Removing the diodes and determining the direction of the resulting current I result in the circuit of Fig. 22. There is a match in current direction for one silicon diode but not for the other silicon diode. The combination of a short circuit in series with an open circuit always results in an open circuit and $I_D = \mathbf{0\text{ A}}$, as shown in Fig. 23.

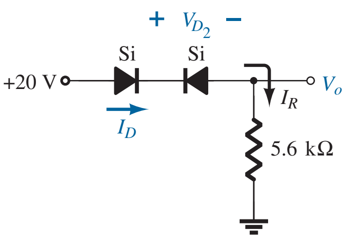


FIG. 21
Circuit for Example 8.

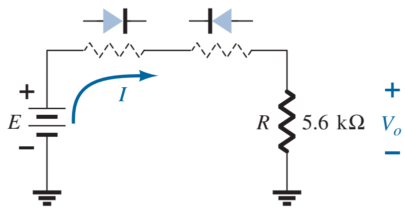


FIG. 22
Determining the state of the diodes of Fig. 21.

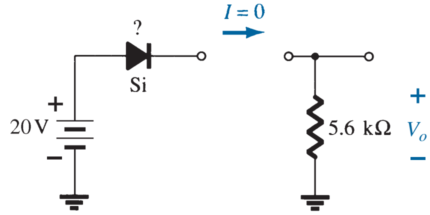


FIG. 23
Substituting the equivalent state for the open diode.

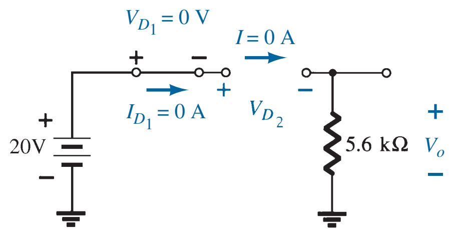


FIG. 24
Determining the unknown quantities for the circuit of Example 8.

The question remains as to what to substitute for the silicon diode. For the analysis to follow in this chapter, simply recall for the actual practical diode that when $I_D = 0$ A, $V_D = 0$ V (and vice versa). The conditions described by $I_D = 0$ A and $V_{D_1} = 0$ V are indicated in Fig. 24. We have

$$V_o = I_R R = I_D R = (0\text{ A})R = \mathbf{0\ V}$$

and
$$V_{D_2} = V_{\text{open circuit}} = E = \mathbf{20\ V}$$

Applying Kirchhoff's voltage law in a clockwise direction gives

$$E - V_{D_1} - V_{D_2} - V_o = 0$$

and
$$V_{D_2} = E - V_{D_1} - V_o = 20\text{ V} - 0 - 0$$
$$= \mathbf{20\ V}$$

with
$$V_o = \mathbf{0\ V}$$

EXAMPLE 9 Determine I, V_1, V_2, and V_o for the series dc configuration of Fig. 25.

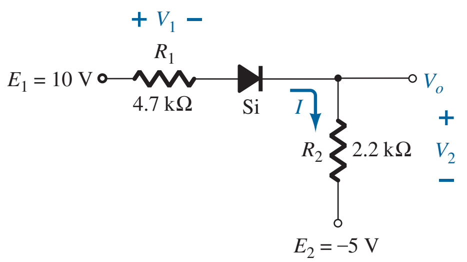


FIG. 25
Circuit for Example 9.

Solution: The sources are drawn and the current direction indicated as shown in Fig. 26. The diode is in the "on" state and the notation appearing in Fig. 27 is included to indicate this state. Note that the "on" state is noted simply by the additional $V_D = 0.7$ V on the figure. This eliminates the need to redraw the network and avoids any confusion that may

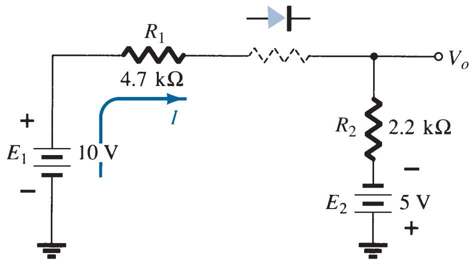


FIG. 26
Determining the state of the diode for the network of Fig. 25.

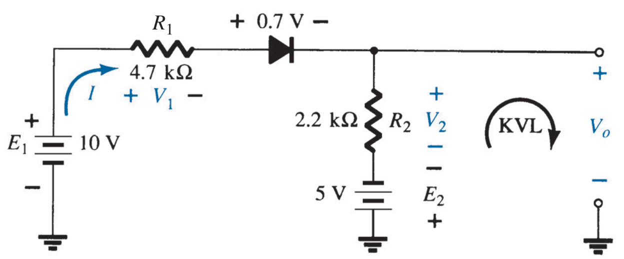


FIG. 27
Determining the unknown quantities for the network of Fig. 25. KVL, Kirchhoff voltage loop.

result from the appearance of another source. As indicated in the introduction to this section, this is probably the path and notation that one will take when a level of confidence has been established in the analysis of diode configurations. In time the entire analysis will be performed simply by referring to the original network. Recall that a reverse-biased diode can simply be indicated by a line through the device.

The resulting current through the circuit is

$$I = \frac{E_1 + E_2 - V_D}{R_1 + R_2} = \frac{10\text{ V} + 5\text{ V} - 0.7\text{ V}}{4.7\text{ k}\Omega + 2.2\text{ k}\Omega} = \frac{14.3\text{ V}}{6.9\text{ k}\Omega}$$
$$\cong \mathbf{2.07\text{ mA}}$$

and the voltages are

$$V_1 = IR_1 = (2.07\text{ mA})(4.7\text{ k}\Omega) = \mathbf{9.73\text{ V}}$$
$$V_2 = IR_2 = (2.07\text{ mA})(2.2\text{ k}\Omega) = \mathbf{4.55\text{ V}}$$

Applying Kirchhoff's voltage law to the output section in the clockwise direction results in

$$-E_2 + V_2 - V_o = 0$$

and $$V_o = V_2 - E_2 = 4.55\text{ V} - 5\text{ V} = \mathbf{-0.45\text{ V}}$$

The minus sign indicates that V_o has a polarity opposite to that appearing in Fig. 25.

4 PARALLEL AND SERIES–PARALLEL CONFIGURATIONS

The methods applied in Section 3 can be extended to the analysis of parallel and series–parallel configurations. For each area of application, simply match the sequential series of steps applied to series diode configurations.

EXAMPLE 10 Determine V_o, I_1, I_{D_1}, and I_{D_2} for the parallel diode configuration of Fig. 28.

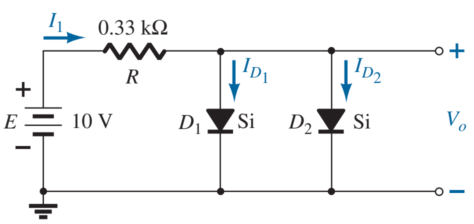


FIG. 28
Network for Example 10.

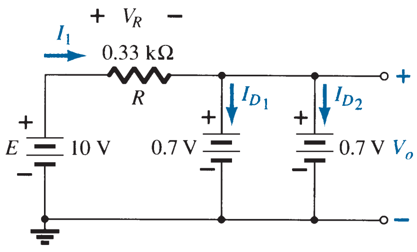


FIG. 29
Determining the unknown quantities for the network of Example 10.

Solution: For the applied voltage the "pressure" of the source acts to establish a current through each diode in the same direction as shown in Fig. 29. Since the resulting current direction matches that of the arrow in each diode symbol and the applied voltage is greater than 0.7 V, both diodes are in the "on" state. The voltage across parallel elements is always the same and

$$V_o = \mathbf{0.7\text{ V}}$$

The current is

$$I_1 = \frac{V_R}{R} = \frac{E - V_D}{R} = \frac{10\text{ V} - 0.7\text{ V}}{0.33\text{ k}\Omega} = \mathbf{28.18\text{ mA}}$$

Assuming diodes of similar characteristics, we have

$$I_{D_1} = I_{D_2} = \frac{I_1}{2} = \frac{28.18\text{ mA}}{2} = \mathbf{14.09\text{ mA}}$$

This example demonstrates one reason for placing diodes in parallel. If the current rating of the diodes of Fig. 28 is only 20 mA, a current of 28.18 mA would damage the device if it appeared alone in Fig. 28. By placing two in parallel, we limit the current to a safe value of 14.09 mA with the same terminal voltage.

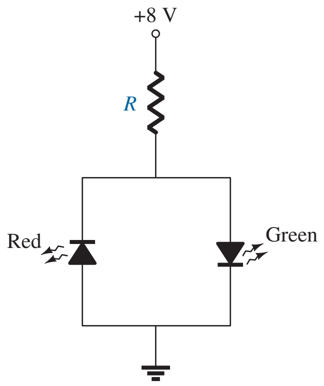


FIG. 30
Network for Example 11.

EXAMPLE 11 In this example there are two LEDs that can be used as a polarity detector. Apply a positive source voltage and a green light results. Negative supplies result in a red light. Packages of such combinations are commercially available.

Find the resistor R to ensure a current of 20 mA through the "on" diode for the configuration of Fig. 30. Both diodes have a reverse breakdown voltage of 3 V and an average turn-on voltage of 2 V.

Solution: The application of a positive supply voltage results in a conventional current that matches the arrow of the green diode and turns it on.

The polarity of the voltage across the green diode is such that it reverse biases the red diode by the same amount. The result is the equivalent network of Fig. 31.

Applying Ohm's law, we obtain

$$I = 20\text{ mA} = \frac{E - V_{\text{LED}}}{R} = \frac{8\text{ V} - 2\text{ V}}{R}$$

and

$$R = \frac{6\text{ V}}{20\text{ mA}} = \mathbf{300\ \Omega}$$

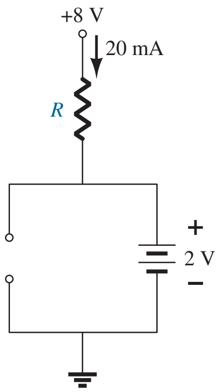


FIG. 31
Operating conditions for the network of Fig. 30.

Note that the reverse breakdown voltage across the red diode is 2 V, which is fine for an LED with a reverse breakdown voltage of 3 V.

However, if the green diode were to be replaced by a blue diode, problems would develop, as shown in Fig. 32. Recall that the forward bias required to turn on a blue diode is about 5 V. The result would appear to require a smaller resistor R to establish the current of 20 mA. However, note that the reverse bias voltage of the red LED is 5 V, but the reverse breakdown voltage of the diode is only 3 V. The result is the voltage across the red LED would lock in at 3 V as shown in Fig. 33. The voltage across R would be 5 V and the current limited to 20 mA with a 250 Ω resistor but neither LED would be on.

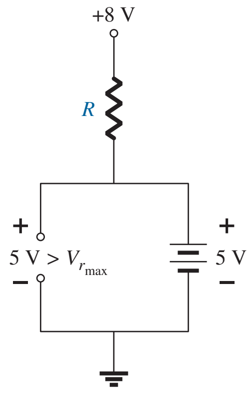


FIG. 32
Network of Fig. 31 with a blue diode.

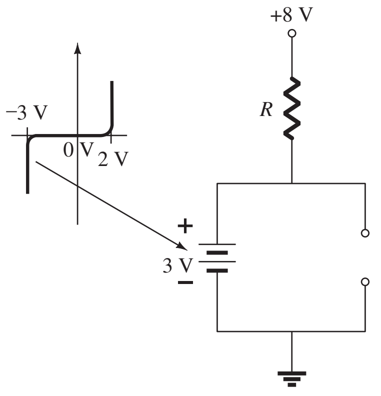


FIG. 33
Demonstrating damage to the red LED if the reverse breakdown voltage is exceeded.

A simple solution to the above is to add the appropriate resistance level in series with each diode to establish the desired 20 mA and to include another diode to add to the reverse-bias total reverse breakdown voltage rating, as shown in Fig. 34. When the blue LED is on, the diode in series with the blue LED will also be on, causing a total voltage drop of 5.7 V across the two series diodes and a voltage of 2.3 V across the resistor R_1, establishing a high emission current of 19.17 mA. At the same time the red LED diode and

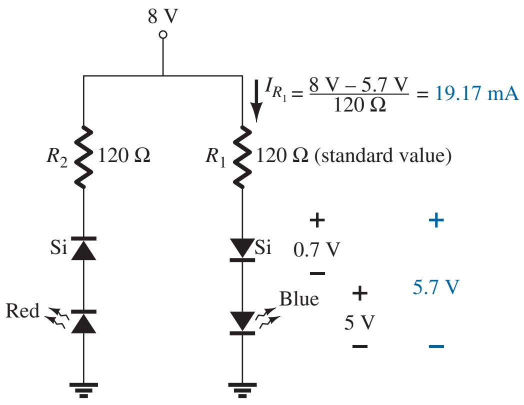


FIG. 34
Protective measure for the red LED of Fig. 33.

its series diode will also be reverse biased, but now the standard diode with a reverse breakdown voltage of 20 V will prevent the full reverse-bias voltage of 8 V from appearing across the red LED. When forward biased, the resistor R_2 will establish a current of 19.63 mA to ensure a high level of intensity for the red LED.

EXAMPLE 12 Determine the voltage V_o for the network of Fig. 35.

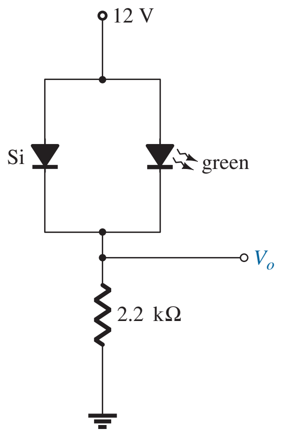


FIG. 35
Network for Example 12.

Solution: Initially, it might appear that the applied voltage will turn both diodes "on" because the applied voltage ("pressure") is trying to establish a conventional current through each diode that would suggest the "on" state. However, if both were on, there would be more than one voltage across the parallel diodes, violating one of the basic rules of network analysis: The voltage must be the same across parallel elements.

The resulting action can best be explained by remembering that there is a period of build-up of the supply voltage from 0 V to 12 V even though it may take milliseconds or microseconds. At the instant the increasing supply voltage reaches 0.7 V the silicon diode will turn "on" and maintain the level of 0.7 V since the characteristic is vertical at this voltage—the current of the silicon diode will simply rise to the defined level. The result is that the voltage across the green LED will never rise above 0.7 V and will remain in the equivalent open-circuit state as shown in Fig. 36.

The result is

$$V_o = 12 \text{ V} - 0.7 \text{ V} = \mathbf{11.3\ V}$$

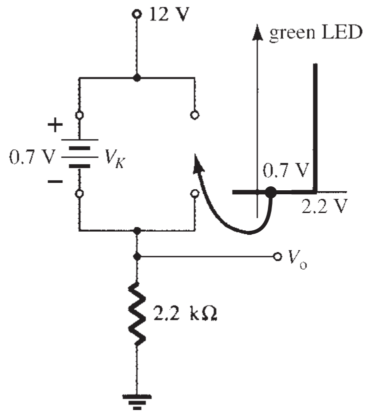


FIG. 36
Determining V_o for the network of Fig. 35.

EXAMPLE 13 Determine the currents I_1, I_2, and I_{D_2} for the network of Fig. 37.

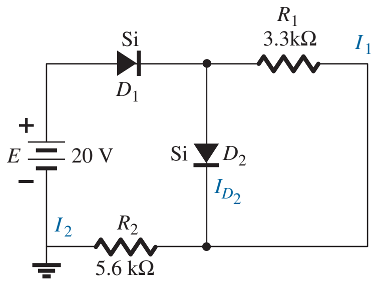


FIG. 37
Network for Example 13.

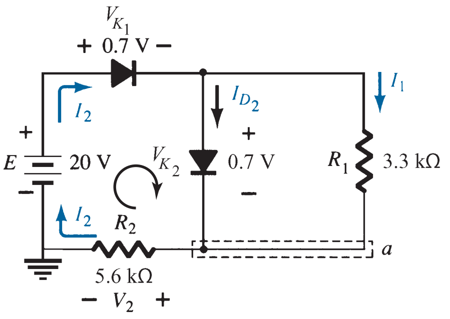


FIG. 38
Determining the unknown quantities for Example 13.

Solution: The applied voltage (pressure) is such as to turn both diodes on, as indicated by the resulting current directions in the network of Fig. 38. Note the use of the abbreviated notation for "on" diodes and that the solution is obtained through an application of techniques applied to dc series–parallel networks. We have

$$I_1 = \frac{V_{K_2}}{R_1} = \frac{0.7\text{ V}}{3.3\text{ k}\Omega} = \mathbf{0.212\text{ mA}}$$

Applying Kirchhoff's voltage law around the indicated loop in the clockwise direction yields

$$-V_2 + E - V_{K_1} - V_{K_2} = 0$$

and $$V_2 = E - V_{K_1} - V_{K_2} = 20\text{ V} - 0.7\text{ V} - 0.7\text{ V} = \mathbf{18.6\text{ V}}$$

with $$I_2 = \frac{V_2}{R_2} = \frac{18.6\text{ V}}{5.6\text{ k}\Omega} = \mathbf{3.32\text{ mA}}$$

At the bottom node a,

$$I_{D_2} + I_1 = I_2$$

and $$I_{D_2} = I_2 - I_1 = 3.32\text{ mA} - 0.212\text{ mA} \cong \mathbf{3.11\text{ mA}}$$

5 AND/OR GATES

The tools of analysis are now at our disposal, and the opportunity to investigate a computer configuration is one that will demonstrate the range of applications of this relatively simple device. Our analysis will be limited to determining the voltage levels and will not include a detailed discussion of Boolean algebra or positive and negative logic.

The network to be analyzed in Example 14 is an OR gate for positive logic. That is, the 10-V level of Fig. 39 is assigned a "1" for Boolean algebra and the 0-V input is assigned a "0." An OR gate is such that the output voltage level will be a 1 if either *or* both inputs is a 1. The output is a 0 if both inputs are at the 0 level.

The analysis of AND/OR gates is made easier by using the approximate equivalent for a diode rather than the ideal because we can stipulate that the voltage across the diode must be 0.7 V positive for the silicon diode to switch to the "on" state.

In general, the best approach is simply to establish a "gut" feeling for the state of the diodes by noting the direction and the "pressure" established by the applied potentials. The analysis will then verify or negate your initial assumptions.

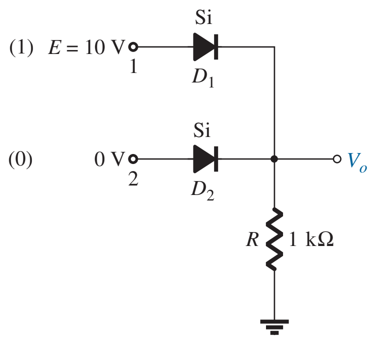


FIG. 39
Positive logic OR gate.

EXAMPLE 14 Determine V_o for the network of Fig. 39.

Solution: First note that there is only one applied potential; 10 V at terminal 1. Terminal 2 with a 0-V input is essentially at ground potential, as shown in the redrawn network of

Fig. 40. Figure 40 "suggests" that D_1 is probably in the "on" state due to the applied 10 V, whereas D_2 with its "positive" side at 0 V is probably "off." Assuming these states will result in the configuration of Fig. 41.

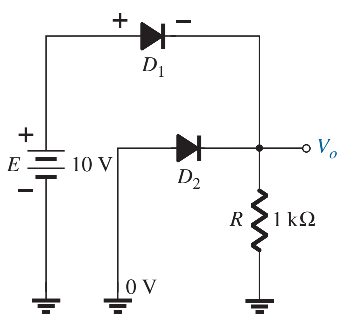


FIG. 40
Redrawn network of Fig. 39.

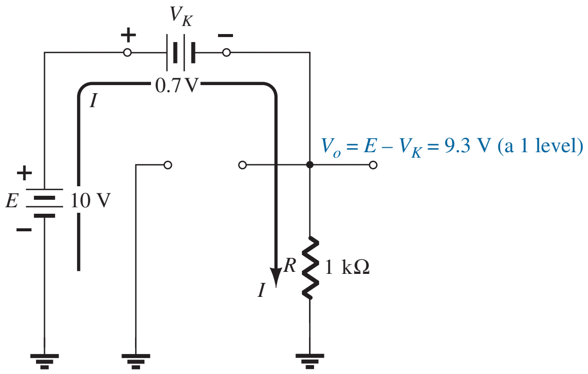


FIG. 41
Assumed diode states for Fig. 40.

The next step is simply to check that there is no contradiction in our assumptions. That is, note that the polarity across D_1 is such as to turn it on and the polarity across D_2 is such as to turn it off. For D_1 the "on" state establishes V_o at $V_o = E - V_D = 10\text{ V} - 0.7\text{ V} = \mathbf{9.3\text{ V}}$. With 9.3 V at the cathode ($-$) side of D_2 and 0 V at the anode ($+$) side, D_2 is definitely in the "off" state. The current direction and the resulting continuous path for conduction further confirm our assumption that D_1 is conducting. Our assumptions seem confirmed by the resulting voltages and current, and our initial analysis can be assumed to be correct. The output voltage level is not 10 V as defined for an input of 1, but the 9.3 V is sufficiently large to be considered a 1 level. The output is therefore at a 1 level with only one input, which suggests that the gate is an OR gate. An analysis of the same network with two 10-V inputs will result in both diodes being in the "on" state and an output of 9.3 V. A 0-V input at both inputs will not provide the 0.7 V required to turn the diodes on, and the output will be a 0 due to the 0-V output level. For the network of Fig. 41 the current level is determined by

$$I = \frac{E - V_D}{R} = \frac{10\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega} = \mathbf{9.3\text{ mA}}$$

EXAMPLE 15 Determine the output level for the positive logic AND gate of Fig. 42. An AND gate is one where a 1 output is only obtained when a 1 input appears at each and every input.

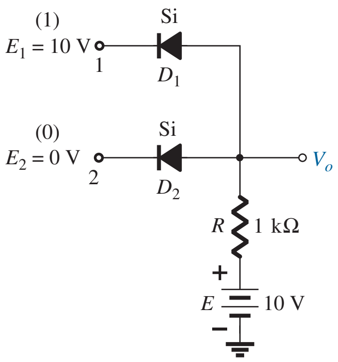


FIG. 42
Positive logic AND gate.

Solution: Note in this case that an independent source appears in the grounded leg of the network. For reasons soon to become obvious, it is chosen at the same level as the input logic level. The network is redrawn in Fig. 43 with our initial assumptions regarding the state of the diodes. With 10 V at the cathode side of D_1 it is assumed that D_1 is in the "off" state even though there is a 10-V source connected to the anode of D_1 through the resistor.

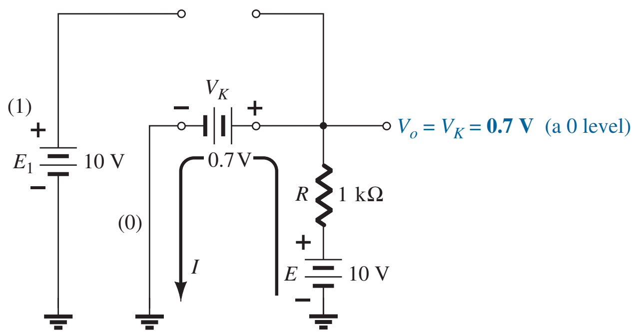


FIG. 43
Substituting the assumed states for the diodes of Fig. 42.

However, recall that we mentioned in the introduction to this section that the use of the approximate model will be an aid to the analysis. For D_1, where will the 0.7 V come from if the input and source voltages are at the same level and creating opposing "pressures"? D_2 is assumed to be in the "on" state due to the low voltage at the cathode side and the availability of the 10-V source through the 1-kΩ resistor.

For the network of Fig. 43 the voltage at V_o is 0.7 V due to the forward-biased diode D_2. With 0.7 V at the anode of D_1 and 10 V at the cathode, D_1 is definitely in the "off" state. The current I will have the direction indicated in Fig. 43 and a magnitude equal to

$$I = \frac{E - V_K}{R} = \frac{10\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega} = \mathbf{9.3\text{ mA}}$$

The state of the diodes is therefore confirmed and our earlier analysis was correct. Although not 0 V as earlier defined for the 0 level, the output voltage is sufficiently small to be considered a 0 level. For the AND gate, therefore, a single input will result in a 0-level output. The remaining states of the diodes for the possibilities of two inputs and no inputs will be examined in the problems at the end of the chapter.

6 SINUSOIDAL INPUTS; HALF-WAVE RECTIFICATION

The diode analysis will now be expanded to include time-varying functions such as the sinusoidal waveform and the square wave. There is no question that the degree of difficulty will increase, but once a few fundamental maneuvers are understood, the analysis will be fairly direct and follow a common thread.

The simplest of networks to examine with a time-varying signal appears in Fig. 44. For the moment we will use the ideal model (note the absence of the Si, Ge, or GaAs label) to ensure that the approach is not clouded by additional mathematical complexity.

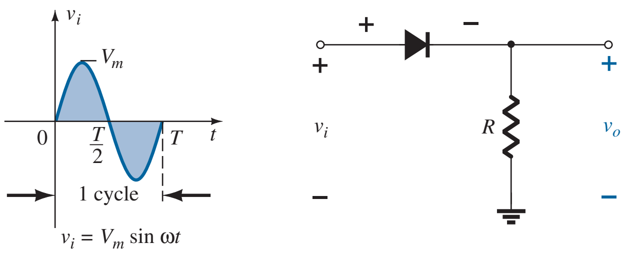


FIG. 44
Half-wave rectifier.

Over one full cycle, defined by the period T of Fig. 44, the average value (the algebraic sum of the areas above and below the axis) is zero. The circuit of Fig. 44, called a *half-wave rectifier*, will generate a waveform v_o that will have an average value of particular use in the ac-to-dc conversion process. When employed in the rectification process, a diode is typically referred to as a *rectifier*. Its power and current ratings are typically much higher than those of diodes employed in other applications, such as computers and communication systems.

During the interval $t = 0 \rightarrow T/2$ in Fig. 44 the polarity of the applied voltage v_i is such as to establish "pressure" in the direction indicated and turn on the diode with the polarity appearing above the diode. Substituting the short-circuit equivalence for the ideal diode will result in the equivalent circuit of Fig. 45, where it is fairly obvious that the output signal is an exact replica of the applied signal. The two terminals defining the output voltage are connected directly to the applied signal via the short-circuit equivalence of the diode.

For the period $T/2 \rightarrow T$, the polarity of the input v_i is as shown in Fig. 46, and the resulting polarity across the ideal diode produces an "off" state with an open-circuit equivalent. The result is the absence of a path for charge to flow, and $v_o = iR = (0)R = 0$ V for the period $T/2 \rightarrow T$. The input v_i and the output v_o are sketched together in Fig. 47 for comparison purposes. The output signal v_o now has a net positive area above the axis over

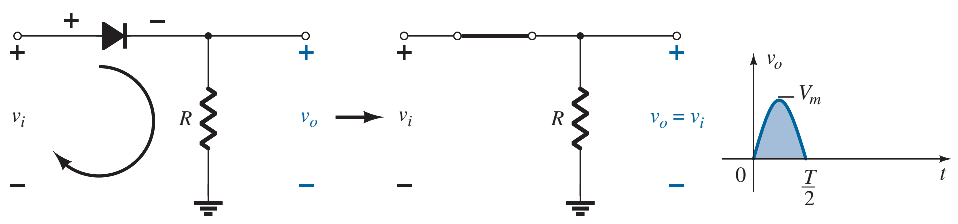


FIG. 45
Conduction region (0 → T/2).

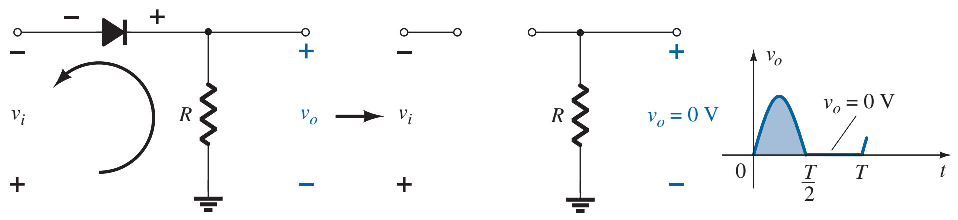


FIG. 46
Nonconduction region (T/2 → T).

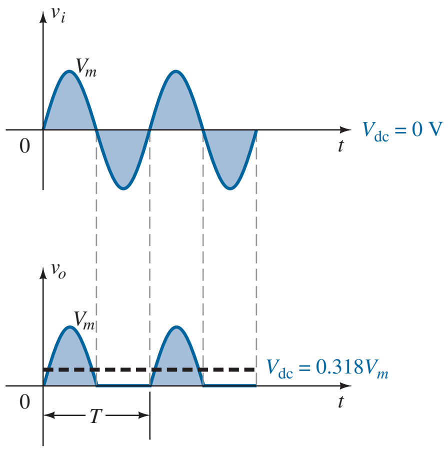


FIG. 47
Half-wave rectified signal.

a full period and an average value determined by

$$\boxed{V_{dc} = 0.318\,V_m} \quad \text{half-wave} \tag{7}$$

The process of removing one-half the input signal to establish a dc level is called *half-wave rectification*.

The effect of using a silicon diode with $V_K = 0.7$ V is demonstrated in Fig. 48 for the forward-bias region. The applied signal must now be at least 0.7 V before the diode can turn "on." For levels of v_i less than 0.7 V, the diode is still in an open-circuit state and $v_o = 0$ V, as shown in the same figure. When conducting, the difference between v_o and v_i is a fixed

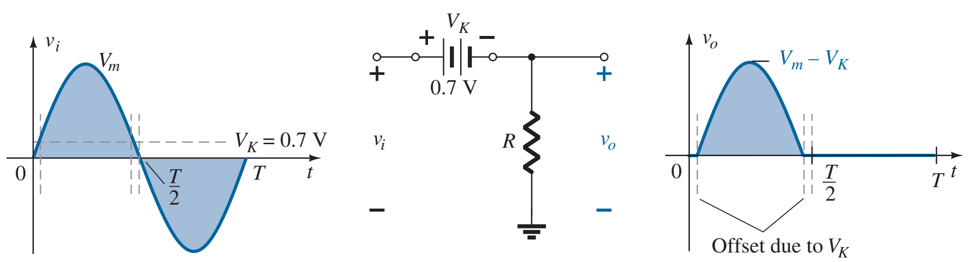


FIG. 48
Effect of V_K on half-wave rectified signal.

level of $V_K = 0.7$ V and $v_o = v_i - V_K$, as shown in the figure. The net effect is a reduction in area above the axis, which reduces the resulting dc voltage level. For situations where $V_m \gg V_K$, the following equation can be applied to determine the average value with a relatively high level of accuracy.

$$\boxed{V_{dc} \cong 0.318(V_m - V_K)} \tag{8}$$

In fact, if V_m is sufficiently greater than V_K, Eq. (7) is often applied as a first approximation for V_{dc}.

EXAMPLE 16

a. Sketch the output v_o and determine the dc level of the output for the network of Fig. 49.
b. Repeat part (a) if the ideal diode is replaced by a silicon diode.
c. Repeat parts (a) and (b) if V_m is increased to 200 V, and compare solutions using Eqs. (7) and (8).

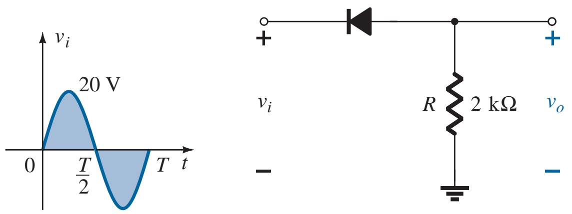


FIG. 49
Network for Example 16.

Solution:

a. In this situation the diode will conduct during the negative part of the input as shown in Fig. 50, and v_o will appear as shown in the same figure. For the full period, the dc level is

$$V_{dc} = -0.318V_m = -0.318(20 \text{ V}) = \mathbf{-6.36\ V}$$

The negative sign indicates that the polarity of the output is opposite to the defined polarity of Fig. 49.

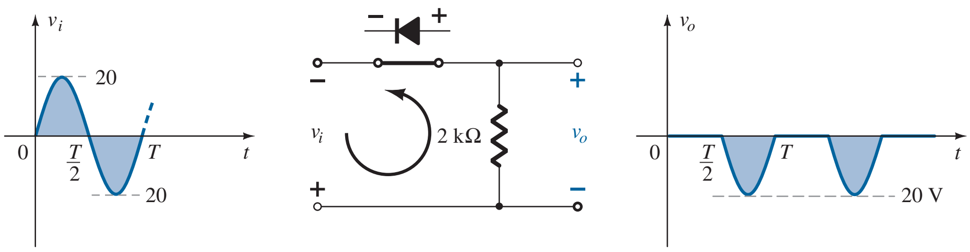


FIG. 50
Resulting v_o for the circuit of Example 16.

b. For a silicon diode, the output has the appearance of Fig. 51, and

$$V_{dc} \cong -0.318(V_m - 0.7 \text{ V}) = -0.318(19.3 \text{ V}) \cong \mathbf{-6.14\ V}$$

The resulting drop in dc level is 0.22 V, or about 3.5%.

c. Eq. (7): $V_{dc} = -0.318\ V_m = -0.318(200 \text{ V}) = \mathbf{-63.6\ V}$

Eq. (8): $V_{dc} = -0.318(V_m - V_K) = -0.318(200 \text{ V} - 0.7 \text{ V})$

$= -(0.318)(199.3 \text{ V}) = \mathbf{-63.38\ V}$

which is a difference that can certainly be ignored for most applications. For part (c) the offset and drop in amplitude due to V_K would not be discernible on a typical oscilloscope if the full pattern is displayed.

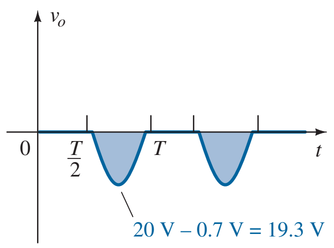


FIG. 51
Effect of V_K on output of Fig. 50.

PIV (PRV)

The peak inverse voltage (PIV) [or PRV (peak reverse voltage)] rating of the diode is of primary importance in the design of rectification systems. Recall that it is the voltage rating that must not be exceeded in the reverse-bias region or the diode will enter the Zener avalanche region. The required PIV rating for the half-wave rectifier can be determined from Fig. 52, which displays the reverse-biased diode of Fig. 44 with maximum applied voltage. Applying Kirchhoff's voltage law, it is fairly obvious that the PIV rating of the diode must equal or exceed the peak value of the applied voltage. Therefore,

$$\boxed{\text{PIV rating} \geqq V_m} \quad \text{half-wave rectifier} \qquad \textbf{(9)}$$

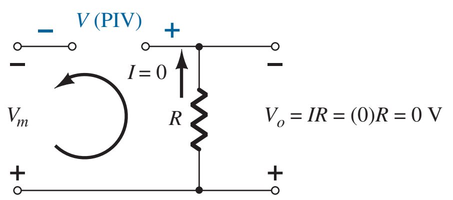


FIG. 52
Determining the required PIV rating for the half-wave rectifier.

7 FULL-WAVE RECTIFICATION

Bridge Network

The dc level obtained from a sinusoidal input can be improved 100% using a process called *full-wave rectification*. The most familiar network for performing such a function appears in Fig. 53 with its four diodes in a *bridge* configuration. During the period $t = 0$ to $T/2$ the polarity of the input is as shown in Fig. 54. The resulting polarities across the ideal diodes are also shown in Fig. 54 to reveal that D_2 and D_3 are conducting, whereas D_1 and D_4 are in the "off" state. The net result is the configuration of Fig. 55, with its indicated current and polarity across R. Since the diodes are ideal, the load voltage is $v_o = v_i$, as shown in the same figure.

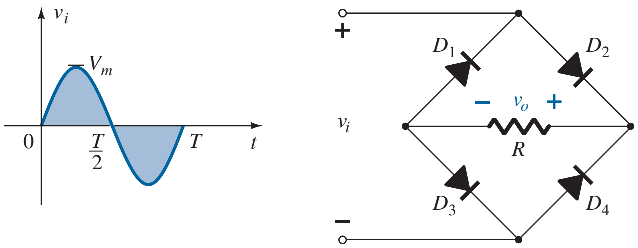


FIG. 53
Full-wave bridge rectifier.

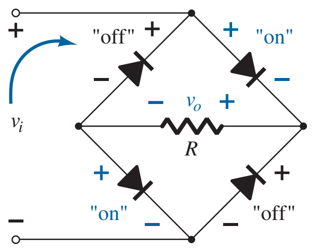


FIG. 54
Network of Fig. 53 for the period $0 \rightarrow T/2$ of the input voltage v_i.

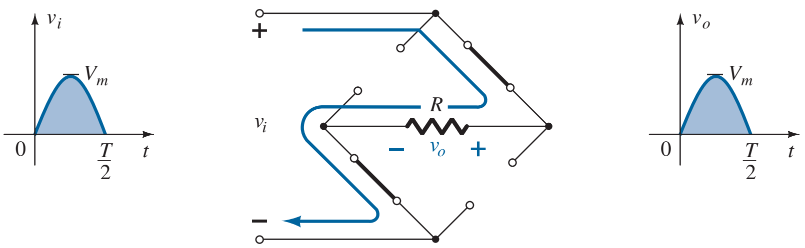


FIG. 55
Conduction path for the positive region of v_i.

For the negative region of the input the conducting diodes are D_1 and D_4, resulting in the configuration of Fig. 56. The important result is that the polarity across the load resistor R is the same as in Fig. 54, establishing a second positive pulse, as shown in Fig. 56. Over one full cycle the input and output voltages will appear as shown in Fig. 57.

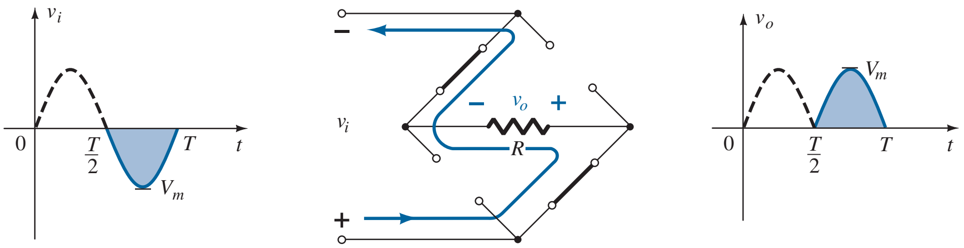


FIG. 56
Conduction path for the negative region of v_i.

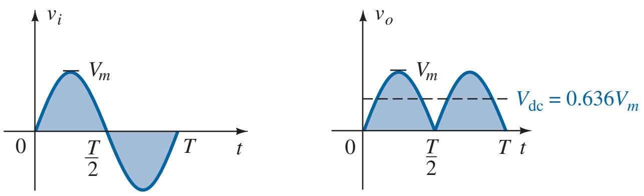


FIG. 57
Input and output waveforms for a full-wave rectifier.

Since the area above the axis for one full cycle is now twice that obtained for a half-wave system, the dc level has also been doubled and

$$V_{dc} = 2[\text{Eq. (7)}] = 2(0.318V_m)$$

or $$\boxed{V_{dc} = 0.636\,V_m} \quad \text{full-wave} \qquad \textbf{(10)}$$

If silicon rather than ideal diodes are employed as shown in Fig. 58, the application of Kirchhoff's voltage law around the conduction path results in

$$v_i - V_K - v_o - V_K = 0$$

and $$v_o = v_i - 2V_K$$

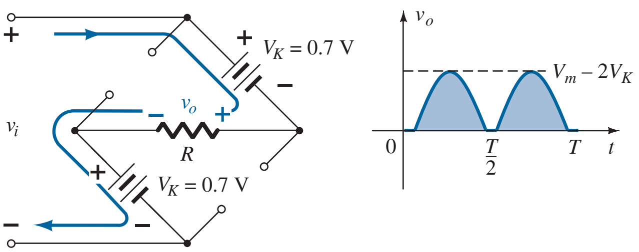


FIG. 58
Determining $V_{o_{max}}$ for silicon diodes in the bridge configuration.

The peak value of the output voltage v_o is therefore

$$V_{o_{max}} = V_m - 2V_K$$

For situations where $V_m \gg 2V_K$, the following equation can be applied for the average value with a relatively high level of accuracy:

$$\boxed{V_{dc} \cong 0.636(V_m - 2V_K)} \qquad \textbf{(11)}$$

Then again, if V_m is sufficiently greater than $2V_K$, then Eq. (10) is often applied as a first approximation for V_{dc}.

PIV The required PIV of each diode (ideal) can be determined from Fig. 59 obtained at the peak of the positive region of the input signal. For the indicated loop the maximum voltage across R is V_m and the PIV rating is defined by

$$\boxed{\text{PIV} \geqq V_m} \quad \text{full-wave bridge rectifier} \tag{12}$$

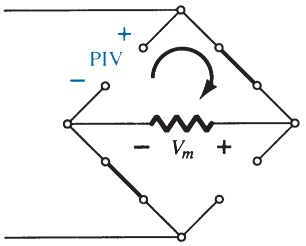


FIG. 59
Determining the required PIV for the bridge configuration.

Center-Tapped Transformer

A second popular full-wave rectifier appears in Fig. 60 with only two diodes but requiring a center-tapped (CT) transformer to establish the input signal across each section of the secondary of the transformer. During the positive portion of v_i applied to the primary of the transformer, the network will appear as shown in Fig. 61 with a positive pulse across each section of the secondary coil. D_1 assumes the short-circuit equivalent and D_2 the open-circuit equivalent, as determined by the secondary voltages and the resulting current directions. The output voltage appears as shown in Fig. 61.

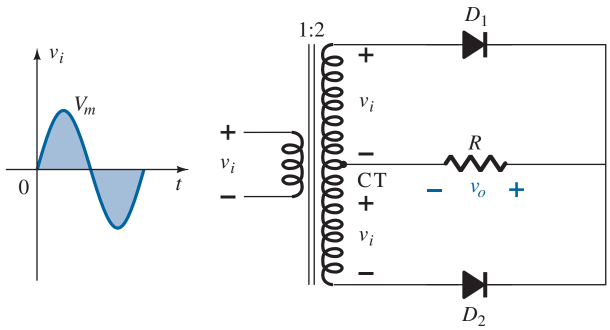


FIG. 60
Center-tapped transformer full-wave rectifier.

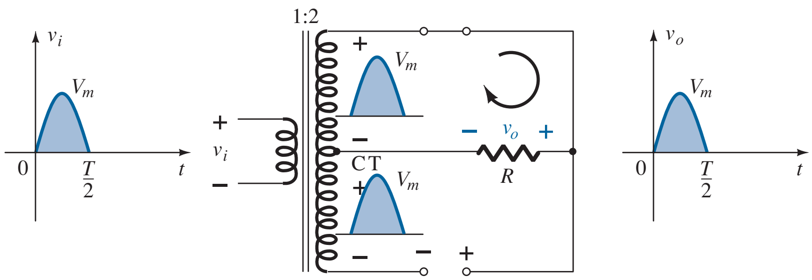


FIG. 61
Network conditions for the positive region of v_i.

During the negative portion of the input the network appears as shown in Fig. 62, reversing the roles of the diodes but maintaining the same polarity for the voltage across the load resistor R. The net effect is the same output as that appearing in Fig. 57 with the same dc levels.

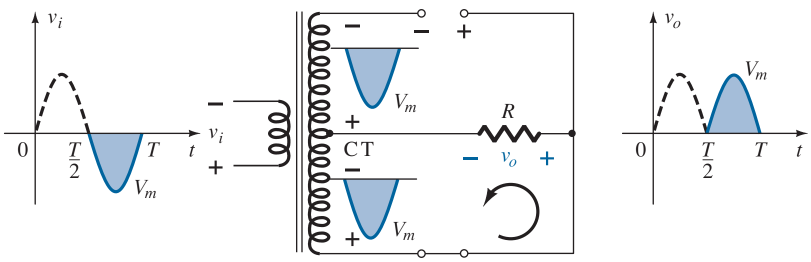


FIG. 62
Network conditions for the negative region of v_i.

PIV The network of Fig. 63 will help us determine the net PIV for each diode for this full-wave rectifier. Inserting the maximum voltage for the secondary voltage and V_m as established by the adjoining loop results in

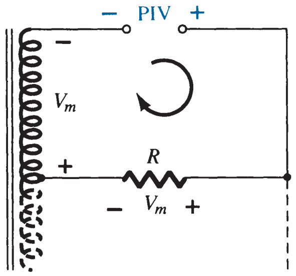


FIG. 63
Determining the PIV level for the diodes of the CT transformer full-wave rectifier.

$$\begin{aligned} \text{PIV} &= V_{\text{secondary}} + V_R \\ &= V_m + V_m \end{aligned}$$

and $$\boxed{\text{PIV} \geqq 2V_m} \quad \text{CT transformer, full-wave rectifier} \tag{13}$$

EXAMPLE 17 Determine the output waveform for the network of Fig. 64 and calculate the output dc level and the required PIV of each diode.

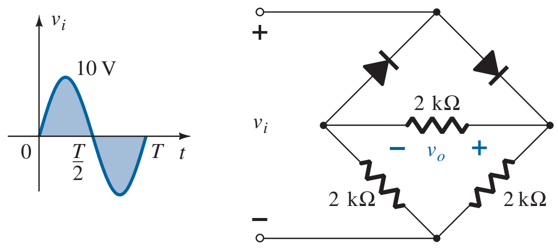


FIG. 64
Bridge network for Example 17.

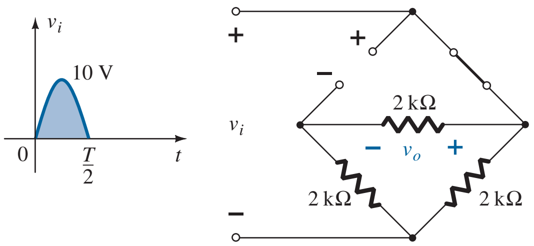


FIG. 65
Network of Fig. 64 for the positive region of v_i.

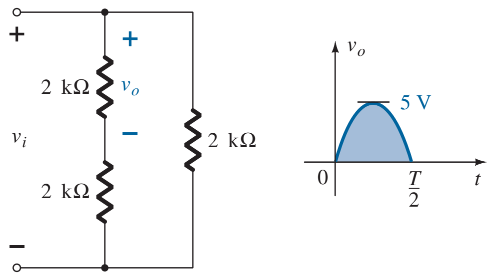


FIG. 66
Redrawn network of Fig. 65.

Solution: The network appears as shown in Fig. 65 for the positive region of the input voltage. Redrawing the network results in the configuration of Fig. 66, where $v_o = \frac{1}{2}v_i$ or $V_{o_{\max}} = \frac{1}{2}V_{i_{\max}} = \frac{1}{2}(10\text{ V}) = 5\text{ V}$, as shown in Fig. 66. For the negative part of the input, the roles of the diodes are interchanged and v_o appears as shown in Fig. 67.

The effect of removing two diodes from the bridge configuration is therefore to reduce the available dc level to the following:

$$V_{\text{dc}} = 0.636(5\text{ V}) = \mathbf{3.18\ V}$$

or that available from a half-wave rectifier with the same input. However, the PIV as determined from Fig. 59 is equal to the maximum voltage across R, which is 5 V, or half of that required for a half-wave rectifier with the same input.

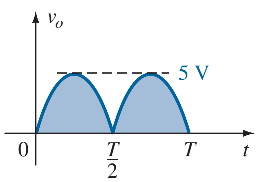


FIG. 67
Resulting output for Example 17.

8 CLIPPERS

The previous section on rectification gives clear evidence that diodes can be used to change the appearance of an applied waveform. This section on clippers and the next on clampers will expand on the wave-shaping abilities of diodes.

Clippers are networks that employ diodes to "clip" away a portion of an input signal without distorting the remaining part of the applied waveform.

The half-wave rectifier of Section 6 is an example of the simplest form of diode clipper—one resistor and a diode. Depending on the orientation of the diode, the positive or negative region of the applied signal is "clipped" off.

There are two general categories of clippers: *series* and *parallel.* The series configuration is defined as one where the diode is in series with the load, whereas the parallel variety has the diode in a branch parallel to the load.

Series

The response of the series configuration of Fig. 68a to a variety of alternating waveforms is provided in Fig. 68b. Although first introduced as a half-wave rectifier (for sinusoidal waveforms), there are no boundaries on the type of signals that can be applied to a clipper.

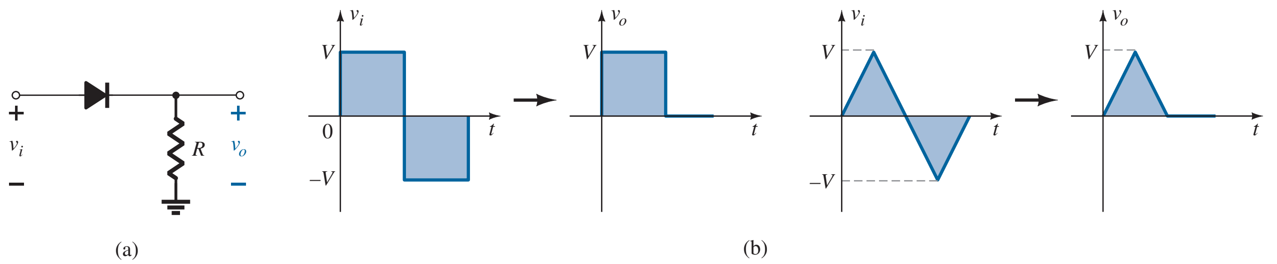


FIG. 68
Series clipper.

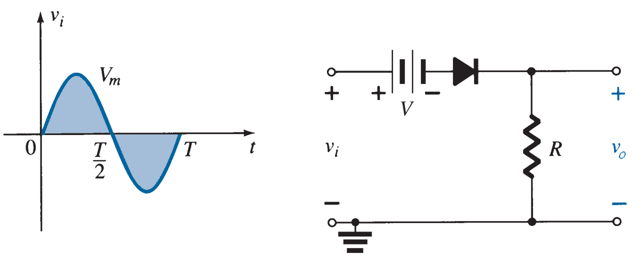


FIG. 69
Series clipper with a dc supply.

The addition of a dc supply to the network as shown in Fig. 69 can have a pronounced effect on the analysis of the series clipper configuration. The response is not as obvious because the dc supply can aid or work against the source voltage, and the dc supply can be in the leg between the supply and output or in the branch parallel to the output.

There is no general procedure for analyzing networks such as the type in Fig. 69, but there are some things one can do to give the analysis some direction.

First and most important:

1. Take careful note of where the output voltage is defined.

In Fig. 69 it is directly across the resistor R. In some cases it may be across a combination of series elements.

Next:

2. Try to develop an overall sense of the response by simply noting the "pressure" established by each supply and the effect it will have on the conventional current direction through the diode.

In Fig. 69, for instance, any positive voltage of the supply will try to turn the diode on by establishing a conventional current through the diode that matches the arrow in the diode symbol. However, the added dc supply V will oppose that applied voltage and try to keep the diode in the "off" state. The result is that any supply voltage greater than V volts will turn the diode on and conduction can be established through the load resistor. Keep in mind that we are dealing with an ideal diode for the moment, so the turn-on voltage is simply 0 V. In general, therefore, for the network of Fig. 69 we can conclude that the diode will be on for any voltage v_i that is greater than V volts and off for any lesser voltage. For the "off" condition, the output would be 0 V due to the lack of current, and for the "on" condition it would simply be $v_o = v_i - V$ as determined by Kirchhoff's voltage law.

3. **Determine the applied voltage (transition voltage) that will result in a change of state for the diode from the "off" to the "on" state.**

This step will help to define a region of the applied voltage when the diode is on and when it is off. On the characteristics of an ideal diode this will occur when $V_D = 0$ V and $I_D = 0$ mA. For the approximate equivalent this is determined by finding the applied voltage when the diode has a drop of 0.7 V across it (for silicon) and $I_D = 0$ mA.

This exercise was applied to the network of Fig. 69 as shown in Fig. 70. Note the substitution of the short-circuit equivalent for the diode and the fact that the voltage across the resistor is 0 V because the diode current is 0 mA. The result is $v_i - V = 0$, and so

$$\boxed{v_i = V} \qquad \textbf{(14)}$$

is the transition voltage.

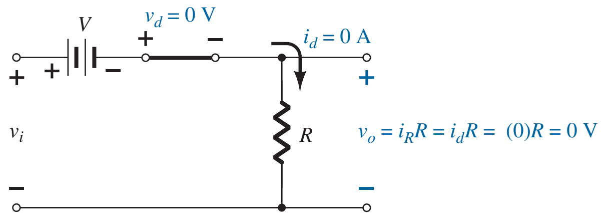


FIG. 70
Determining the transition level for the circuit of Fig. 69.

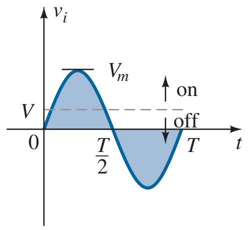


FIG. 71
Using the transition voltage to define the "on" and "off" regions.

This permits drawing a line on the sinusoidal supply voltage as shown in Fig. 71 to define the regions where the diode is on and off.

For the "on" region, as shown in Fig. 72, the diode is replaced by a short-circuit equivalent, and the output voltage is defined by

$$\boxed{v_o = v_i - V} \qquad \textbf{(15)}$$

For the "off" region, the diode is an open circuit, $I_D = 0$ mA, and the output voltage is

$$\boxed{v_o = 0\text{ V}}$$

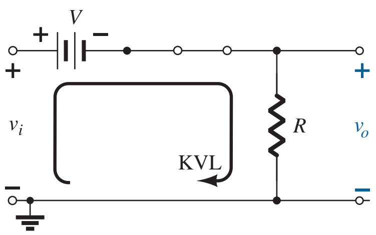


FIG. 72
Determining v_o for the diode in the "on" state.

4. **It is often helpful to draw the output waveform directly below the applied voltage using the same scales for the horizontal axis and the vertical axis.**

Using this last piece of information, we can establish the 0-V level on the plot of Fig. 73 for the region indicated. For the "on" condition, Eq. (15) can be used to find the output voltage when the applied voltage has its peak value:

$$v_{o_{\text{peak}}} = V_m - V$$

and this can be added to the plot of Fig. 73. It is then simple to fill in the missing section of the output curve.

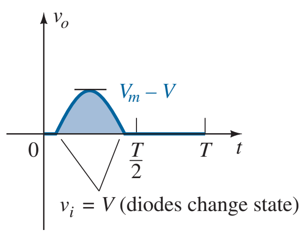


FIG. 73
Sketching the waveform of v_o using the results obtained for v_o above and below the transition level.

EXAMPLE 18 Determine the output waveform for the sinusoidal input of Fig. 74.

Solution:

Step 1: The output is again directly across the resistor R.

Step 2: The positive region of v_i and the dc supply are both applying "pressure" to turn the diode on. The result is that we can safely assume the diode is in the "on" state for the entire range of positive voltages for v_i. Once the supply goes negative, it would have to exceed the dc supply voltage of 5 V before it could turn the diode off.

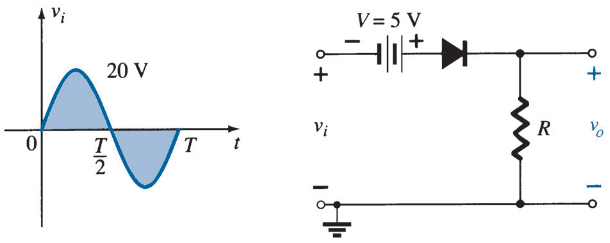


FIG. 74
Series clipper for Example 18.

Step 3: The transition model is substituted in Fig. 75, and we find that the transition from one state to the other will occur when

$$v_i + 5\text{ V} = 0\text{ V}$$

or

$$v_i = -5\text{ V}$$

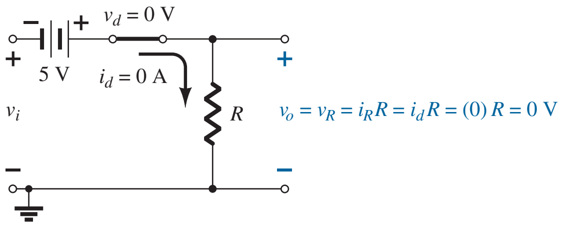


FIG. 75
Determining the transition level for the clipper of Fig. 74.

Step 4: In Fig. 76 a horizontal line is drawn through the applied voltage at the transition level. For voltages less than −5 V the diode is in the open-circuit state and the output is 0 V, as shown in the sketch of v_o. Using Fig. 76, we find that for conditions when the diode is on and the diode current is established the output voltage will be the following, as determined using Kirchhoff's voltage law:

$$v_o = v_i + 5\text{ V}$$

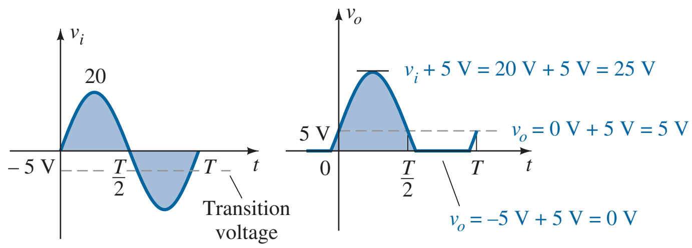


FIG. 76
Sketching v_o for Example 18.

The analysis of clipper networks with square-wave inputs is actually easier than with sinusoidal inputs because only two levels have to be considered. In other words, the network can be analyzed as if it had two dc level inputs with the resulting v_o plotted in the proper time frame. The next example demonstrates the procedure.

EXAMPLE 19 Find the output voltage for the network examined in Example 18 if the applied signal is the square wave of Fig. 77.

Solution: For $v_i = 20\text{ V}\ (0 \rightarrow T/2)$ the network of Fig. 78 results. The diode is in the short-circuit state, and $v_o = 20\text{ V} + 5\text{ V} = 25\text{ V}$. For $v_i = -10\text{ V}$ the network of Fig. 79

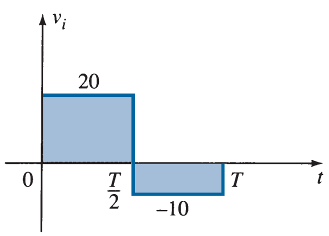


FIG. 77
Applied signal for Example 19.

results, placing the diode in the "off" state, and $v_o = i_R R = (0)R = 0$ V. The resulting output voltage appears in Fig. 80.

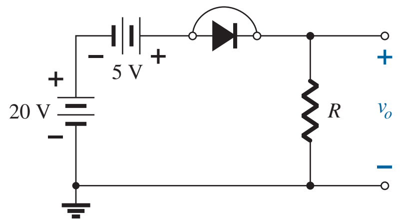


FIG. 78
v_o at $v_i = +20$ V.

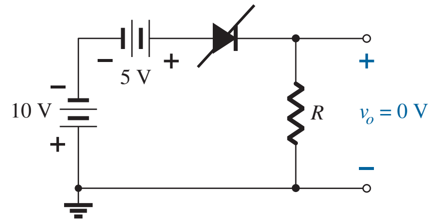


FIG. 79
v_o at $v_i = -10$ V.

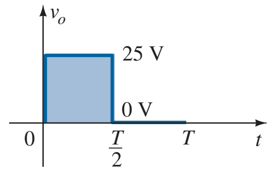


FIG. 80
Sketching v_o for Example 19.

Note in Example 19 that the clipper not only clipped off 5 V from the total swing, but also raised the dc level of the signal by 5 V.

Parallel

The network of Fig. 81 is the simplest of parallel diode configurations with the output for the same inputs of Fig. 68. The analysis of parallel configurations is very similar to that applied to series configurations, as demonstrated in the next example.

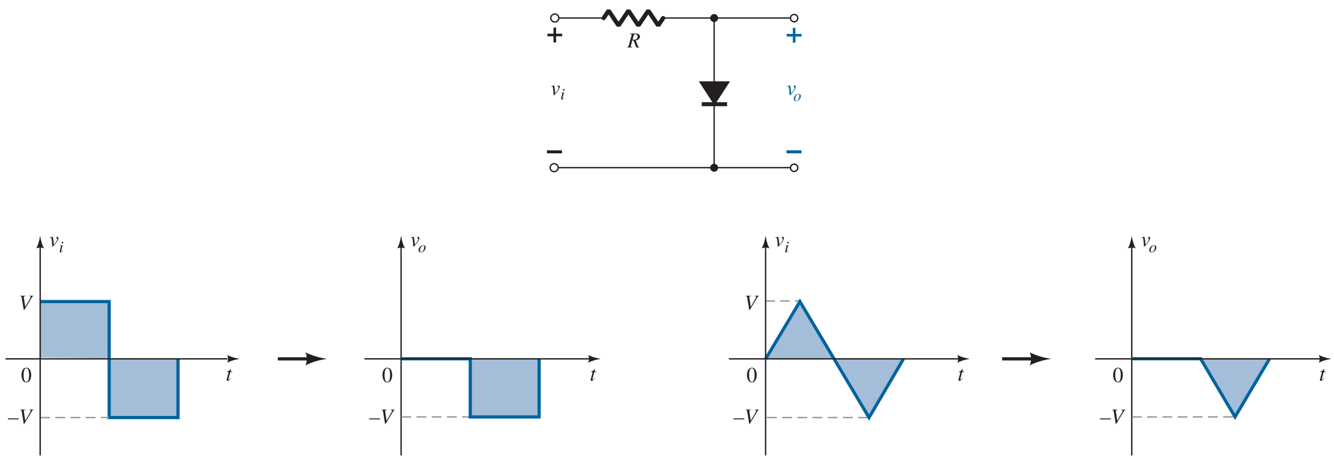


FIG. 81
Response to a parallel clipper.

EXAMPLE 20 Determine v_o for the network of Fig. 82.

Solution:

Step 1: In this example the output is defined across the series combination of the 4-V supply and the diode, not across the resistor R.

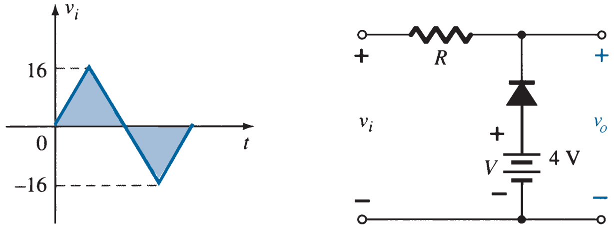


FIG. 82
Example 20.

Step 2: The polarity of the dc supply and the direction of the diode strongly suggest that the diode will be in the "on" state for a good portion of the negative region of the input signal. In fact, it is interesting to note that since the output is directly across the series combination, when the diode is in its short-circuit state the output voltage will be directly across the 4-V dc supply, requiring that the output be fixed at 4 V. In other words, when the diode is on the output will be 4 V. Other than that, when the diode is an open circuit, the current through the series network will be 0 mA and the voltage drop across the resistor will be 0 V. That will result in $v_o = v_i$ whenever the diode is off.

Step 3: The transition level of the input voltage can be found from Fig. 83 by substituting the short-circuit equivalent and remembering the diode current is 0 mA at the instant of transition. The result is a change in state when

$$v_i = 4\text{ V}$$

Step 4: In Fig. 84 the transition level is drawn along with $v_o = 4$ V when the diode is on. For $v_i \geq 4$ V, $v_o = 4$ V, and the waveform is simply repeated on the output plot.

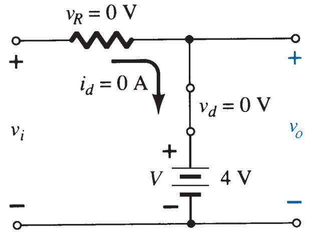


FIG. 83
Determining the transition level for Example 20.

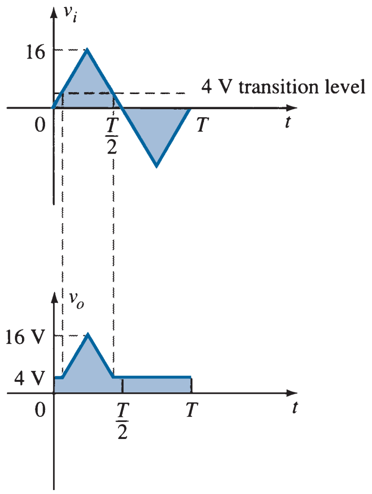


FIG. 84
Sketching v_o for Example 20.

To examine the effects of the knee voltage V_K of a silicon diode on the output response, the next example will specify a silicon diode rather than the ideal diode equivalent.

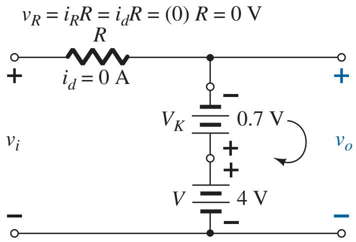


FIG. 85
Determining the transition level for the network of Fig. 82.

EXAMPLE 21 Repeat Example 20 using a silicon diode with $V_K = 0.7$ V.

Solution: The transition voltage can first be determined by applying the condition $i_d = 0$ A at $v_d = V_D = 0.7$ V and obtaining the network of Fig. 85. Applying Kirchhoff's voltage law around the output loop in the clockwise direction, we find that

$$v_i + V_K - V = 0$$

and $$v_i = V - V_K = 4\text{ V} - 0.7\text{ V} = \mathbf{3.3\ V}$$

For input voltages greater than 3.3 V, the diode will be an open circuit and $v_o = v_i$. For input voltages less than 3.3 V, the diode will be in the "on" state and the network of Fig. 86 results, where

$$v_o = 4\text{ V} - 0.7\text{ V} = \mathbf{3.3\ V}$$

The resulting output waveform appears in Fig. 87. Note that the only effect of V_K was to drop the transition level to 3.3 from 4 V.

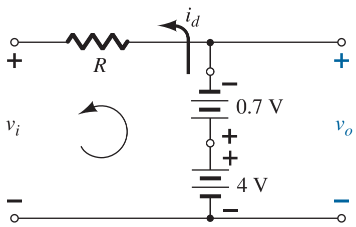


FIG. 86
Determining v_o for the diode of Fig. 82 in the "on" state.

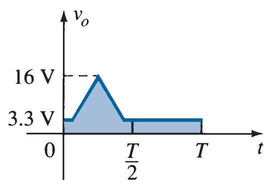


FIG. 87
Sketching v_o for Example 21.

There is no question that including the effects of V_K will complicate the analysis somewhat, but once the analysis is understood with the ideal diode, the procedure, including the effects of V_K, will not be that difficult.

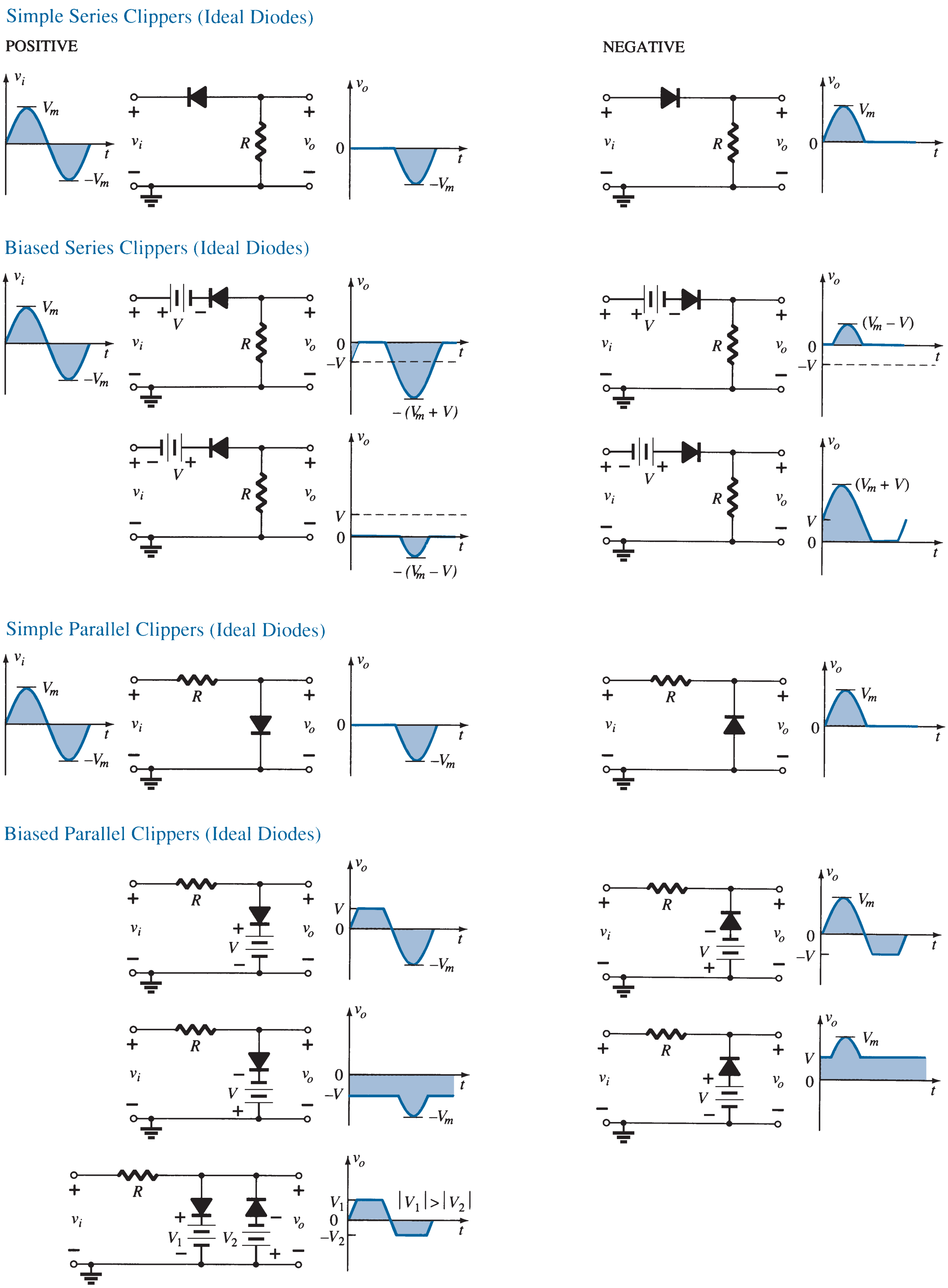


FIG. 88
Clipping circuits.

Summary

A variety of series and parallel clippers with the resulting output for the sinusoidal input are provided in Fig. 88. In particular, note the response of the last configuration, with its ability to clip off a positive and a negative section as determined by the magnitude of the dc supplies.

9 CLAMPERS

The previous section investigated a number of diode configurations that clipped off a portion of the applied signal without changing the remaining part of the waveform. This section will examine a variety of diode configurations that shift the applied signal to a different level.

A clamper is a network constructed of a diode, a resistor, and a capacitor that shifts a waveform to a different dc level without changing the appearance of the applied signal.

Additional shifts can also be obtained by introducing a dc supply to the basic structure. The chosen resistor and capacitor of the network must be chosen such that the time constant determined by $\tau = RC$ is sufficiently large to ensure that the voltage across the capacitor does not discharge significantly during the interval the diode is nonconducting. Throughout the analysis we assume that for all practical purposes the capacitor fully charges or discharges in five time constants.

The simplest of clamper networks is provided in Fig. 89. It is important to note that the capacitor is connected directly between input and output signals and the resistor and the diode are connected in parallel with the output signal.

Clamping networks have a capacitor connected directly from input to output with a resistive element in parallel with the output signal. The diode is also in parallel with the output signal but may or may not have a series dc supply as an added element.

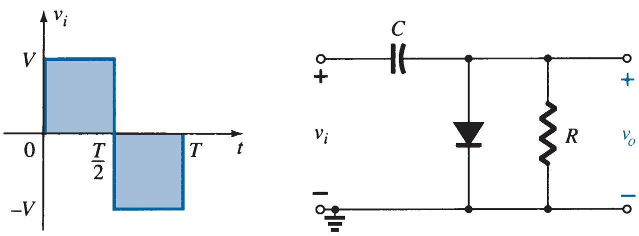


FIG. 89
Clamper.

There is a sequence of steps that can be applied to help make the analysis straightforward. It is not the only approach to examining clampers, but it does offer an option if difficulties surface.

Step 1: Start the analysis by examining the response of the portion of the input signal that will forward bias the diode.
Step 2: During the period that the diode is in the "on" state, assume that the capacitor will charge up instantaneously to a voltage level determined by the surrounding network.

For the network of Fig. 89 the diode will be forward biased for the positive portion of the applied signal. For the interval 0 to $T/2$ the network will appear as shown in Fig. 90. The short-circuit equivalent for the diode will result in $v_o = 0$ V for this time interval, as shown in the sketch of v_o in Fig. 92. During this same interval of time, the time constant determined by $\tau = RC$ is very small because the resistor R has been effectively "shorted out" by the conducting diode and the only resistance present is the inherent (contact, wire) resistance of the network. The result is that the capacitor will quickly charge to the peak value of V volts as shown in Fig. 90 with the polarity indicated.

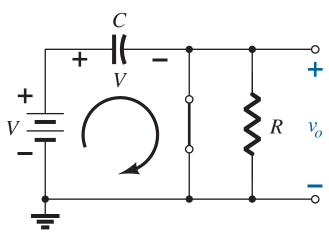


FIG. 90
Diode "on" and the capacitor charging to V volts.

Step 3: Assume that during the period when the diode is in the "off" state the capacitor holds on to its established voltage level.

Step 4: Throughout the analysis, maintain a continual awareness of the location and defined polarity for v_o to ensure that the proper levels are obtained.

When the input switches to the $-V$ state, the network will appear as shown in Fig. 91, with the open-circuit equivalent for the diode determined by the applied signal and stored voltage across the capacitor—both "pressuring" current through the diode from cathode to anode. Now that R is back in the network the time constant determined by the RC product is sufficiently large to establish a discharge period 5τ, much greater than the period $T/2 \rightarrow T$, and it can be assumed on an approximate basis that the capacitor holds onto all its charge and, therefore, voltage (since $V = Q/C$) during this period.

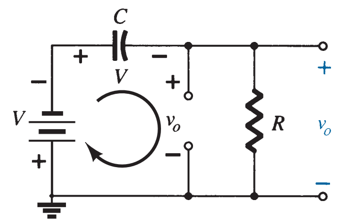


FIG. 91
Determining v_o with the diode "off."

Since v_o is in parallel with the diode and resistor, it can also be drawn in the alternative position shown in Fig. 91. Applying Kirchhoff's voltage law around the input loop results in

$$-V - V - v_o = 0$$

and
$$v_o = -2V$$

The negative sign results from the fact that the polarity of $2V$ is opposite to the polarity defined for v_o. The resulting output waveform appears in Fig. 92 with the input signal. The output signal is clamped to 0 V for the interval 0 to $T/2$ but maintains the same total swing ($2V$) as the input.

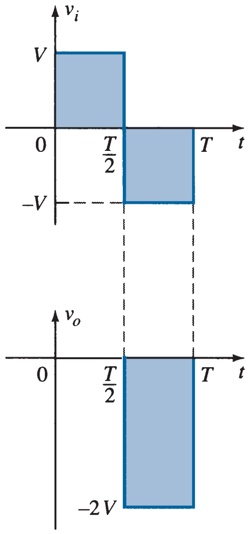


FIG. 92
Sketching v_o for the network of Fig. 91.

Step 5: Check that the total swing of the output matches that of the input.

This is a property that applies for all clamping networks, giving an excellent check on the results obtained.

EXAMPLE 22 Determine v_o for the network of Fig. 93 for the input indicated.

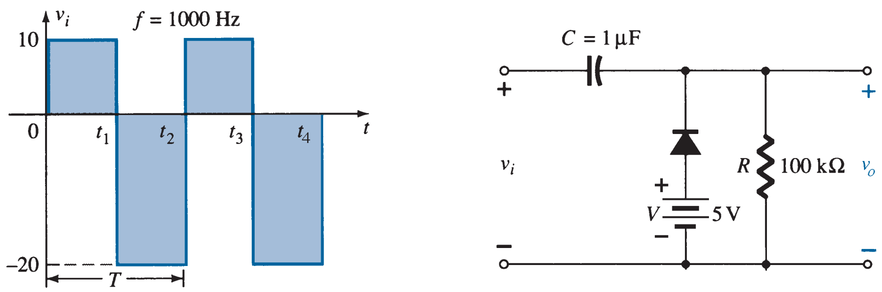


FIG. 93
Applied signal and network for Example 22.

Solution: Note that the frequency is 1000 Hz, resulting in a period of 1 ms and an interval of 0.5 ms between levels. The analysis will begin with the period $t_1 \rightarrow t_2$ of the input signal since the diode is in its short-circuit state. For this interval the network will appear as shown in Fig. 94. The output is across R, but it is also directly across the 5-V battery if one follows the direct connection between the defined terminals for v_o and the battery terminals. The result is $v_o = 5$ V for this interval. Applying Kirchhoff's voltage law around the input loop results in

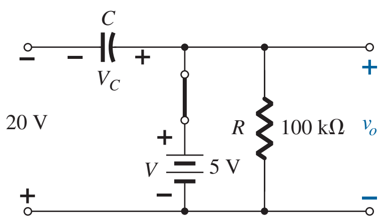


FIG. 94
Determining v_o and V_C with the diode in the "on" state.

$$-20\text{ V} + V_C - 5\text{ V} = 0$$

and
$$V_C = 25\text{ V}$$

The capacitor will therefore charge up to 25 V. In this case the resistor R is not shorted out by the diode, but a Thévenin equivalent circuit of that portion of the network that includes the battery and the resistor will result in $R_{Th} = 0\ \Omega$ with $E_{Th} = V = 5$ V. For the period $t_2 \rightarrow t_3$ the network will appear as shown in Fig. 95.

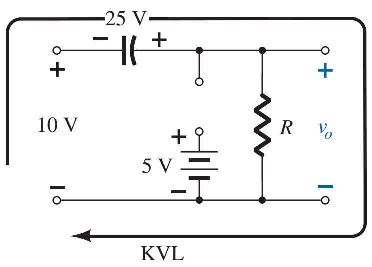


FIG. 95
Determining v_o with the diode in the "off" state.

The open-circuit equivalent for the diode removes the 5-V battery from having any effect on v_o, and applying Kirchhoff's voltage law around the outside loop of the network results in

$$+10\text{ V} + 25\text{ V} - v_o = 0$$

and
$$v_o = 35\text{ V}$$